Muon Detection in CMS: from the Detector Commissioning to the Standard Model Higgs Search

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Introduction

The Large Hadron Collider will start to collide protons at spring of next year and the Compact Muon Solenoid experiment will register the first p-p data, after about 20 years of R&D, design, construction and commissioning. Big expectations are put on the LHC and on its four experiments (ALICE, ATLAS, CMS and LHCB) by the physics community all around the world. Answers to fundamental questions about the nature of the Universe could be around the corner. The hunt for the Higgs boson, the only still undetected particle of the Standard Model (SM) which is in charge to give mass to all the other known fundamental particles, is open. CMS is also competing with ATLAS for the discovery of the Supersymmetric (SUSY) particles, among which there is the most promising candidate to solve the puzzle of the Dark Matter. The SUSY theory can concretise itself in many different models, it’s therefore an elusive theory that waits for an experimental confirmation since the LEP era and before. The LHC is probably able to put the last word to this long search. I would not mention then all the exotic physics models, like Technicolor, Large Extra Dimensions, Little Higgs, which are waiting for the last sentence from the LHC data. It is also possible, however, that the nature has a curve ball in store for us and the LHC will show something completely unexpected.

These big expectations are justified by the unprecedented energy and luminosity that LHC will reach in the next years. In Fig. 1 the energy of LHC is compared with those of previous accelerators: LHC is clearly opening a new era in the experimental high energy physics. On the other side, the luminosity and the energy of LHC put the detectors into a highly challenging experimental environment: huge event rate (40 MHz), overwhelming background (10^9 compared to interesting signals), large radiation dose (e.g., 840 kGy at 4 cm from the interaction point after ~10 years of operation). The detectors deal with this challenge relying on innovative hardware technologies, sophisticated online and offline software algorithms and a revolutionary computing model (based on GRID).

Because of the complexity and the novelty of the experimental undertaking of ATLAS and CMS, it is of primary importance to have a benchmark strategy to rely on, a reference point to start from. CMS, as its name says, has bet
on muons. They are expected to be the most precise and clean signature: for instance the \( H \rightarrow 4\mu \) process should be the “golden channel” for the Higgs discovery.

This thesis is focused on muons: after a general introduction in Chapter 1 about LHC and the CMS detector and physics program, the expected CMS performances on muon detection, trigger and reconstruction are described in Chapter 2. The following chapters describe directly my PhD work.

In the barrel region, CMS has chosen the Drift Tube (DT) technology to detect muons. The algorithms for the calibration and the segment track reconstruction in the DT’s, which I have been working on, are described in Chapter 3 and the expected performances, which I studied using simulated data, are presented (also published in [1, 2]).

Since few years the CMS detector is being commissioned using cosmic muons. These have proved to be very valuable to test hardware operation and software algorithms, although the DT’s have been designed to detect muons coming from the impact point and synchronized with LHC clock. I analyzed the DT calibration and local reconstruction performances with commissioning data considering the particular features of cosmic muons, like random arrival time distribution and track angles not pointing to the impact point. The results obtained with the data taken during the last two years of commissioning are shown in Chapter 3 (also published in [3, 4]).

The muon identification and trigger in the barrel region rely mainly on the DT’s, while the resolution of the offline reconstruction, in the transverse momentum range typical of SM processes (\( p_T < 200 \) GeV), takes big advantage of the inner tracker detector. Beside having the best possible resolution performances, it’s also more important to have a precise knowledge and a steady control of these performances, possibly measuring them from data and not relying only on detector simulations. I developed an algorithm to measure the muon resolution and to calibrate the muon momentum scale exploiting well-known di-muon resonances (\( Z, Y \) and \( J/\psi \)). This algorithm is presented in Chapter 4 and its application for the evaluation of the systematic uncertainties of the \( Z \) cross section measurement is shown (also published in [5]). In this case the calibration of the muon momentum scale strongly reduces the systematics due to misalignment and magnetic field distortion.

Once the muon detector performances and the muon reconstruction systematics will be under control, muons will play a key role in the Higgs search in the intermediate and high-mass regions. As explained in Chapter 5, \( H \rightarrow WW \rightarrow l\nu l\nu \) and \( H \rightarrow ZZ \rightarrow 4l \) are the most promising channels for the Higgs discovery with mass above 140 GeV. I studied a similar channel, \( H \rightarrow ZZ \rightarrow \mu\mu\nu\nu \), which has never been addressed in CMS before. A preliminary exploratory analysis on the feasibility of the Higgs detection in this channel is reported in
Chapter 5 (also published in [6]). The results are very encouraging for very high Higgs mass (500 GeV), in this case about 15.5 fb$^{-1}$ would be enough for a Higgs evidence.

Figure 1: History of accelerators: a selection of the accelerators with highest center of mass energy in each period.
Chapter 1

Physics at the Large Hadron Collider (LHC)

1.1 Why LHC?

The Standard Model (SM) of electroweak interactions has been established experimentally by the observation of neutral current interactions in 1973 at the Gargamelle detector [7] and the observation of the W and Z bosons in 1983 at the UA1 experiment [8]. From 1989 to 2000, the LEP and SLC experiments measured with a better than per-mill precision the properties of the W and Z bosons: their masses, their widths, their couplings with fermions and among themselves. These measurements were complemented by the Tevatron observation of the top quark. The only piece of the SM which is still missing is the Higgs boson, which is the remnant of the scalar field that provide masses to the particles [9]. The precision measurements of the electroweak observables indicate a light Higgs boson. In fact the accuracy reached requires that, when relating them among each other, genuine electroweak quantum corrections $\Delta r$ should be included, namely:

$$m_W^2 = \frac{\pi \alpha_{em}}{G_F \sqrt{2} \sin^2\theta_W (1 - \Delta r)}$$ (1.1)

where the quantum corrections have a quadratic dependence on the mass of the top quark $m_{top}$ and a logarithmic dependence on the mass of the Higgs: $\Delta r = f(m_{top}^2, \ln m_H)$. With $m_W$, $m_{top}$ and $\sin^2\theta_W$ being measured, $m_H$ can be extracted from a global fit of the electroweak observables, as shown in Fig. 1.1. On the other hand the lower limit on the Higgs mass from direct searches at LEP is currently 114.4 GeV at 95% confidence level [10]. Moreover, an upper limit on $m_H$ around 1.2 TeV is derived within the SM requiring that the amplitude for the scattering of longitudinally polarized vector
bosons $V_LV_L \rightarrow V_LV_L$ does not violate unitarity [11].

The Higgs boson is only one of the possibilities to break the symmetry and provide masses to the particles. The Goldstone theorem and the Higgs mechanism do not require the existence of elementary scalars. It is conceivable and widely discussed in the literature that bound states are responsible for electroweak symmetry breaking. Since unitarity is essentially a statement of conservation of total probability it cannot be violated in Nature. Violation of perturbative unitarity implies that the SM becomes a strongly interacting theory at high energy. If the Higgs mass is large or the Higgs is nonexistent, by analogy with low energy QCD, which can be expressed by exactly the same formalism which describes the Higgs sector in the SM, or adopting one of the many schemes for turning perturbative scattering amplitudes into amplitudes which satisfy by construction the unitarity constraints, one is led to expect the presence of resonances in $V_LV_L$ scattering. Unfortunately the mass, spin and even number of these resonances are not uniquely determined.

The discovery of the mechanism which gives origin to the masses requires the deep investigation of the energy range from 100 GeV to 1 TeV. For this reason LHC has been designed as a discovery machine for processes with cross sections...
1.1 Why LHC?

down to some tens of fb and in the energy range from 100 GeV to 1-2 TeV. This physics goal influenced the main design parameters of the machine [12].

- It is a hadron collider: the fundamental constituents entering in the scattering are the partons which carry a variable fraction $x$ of the beam four-momentum. Therefore the center-of-mass energy of the hard scattering process $\sqrt{s}$ can span different orders of magnitude. The center-of-mass energy is $\sqrt{s}=14$ TeV. In this way, incoming partons carrying momentum fractions $x_1, x_2 \approx 0.15-0.20$ of the incoming protons momenta, yield a partonic CM energy $\hat{s} = x_1 x_2 s \approx 1-2$ TeV, the energy range to be explored.

- It is a proton-proton ($p-p$) collider. With respect to an electron-positron machine, it is easier to accelerate protons to high energy since the energy lost for synchrotron radiation, proportional to $\gamma^4$ (where $\gamma = E/m$), is much lower than for the electrons. With respect to a proton-antiproton machine, it is easier to accumulate high intensity beam of protons. Furthermore, the Higgs production process is dominated by gluon fusion, and therefore its cross section is nearly the same in proton-antiproton and $p-p$ collision.

- To compensate for the low cross section of the interesting processes the LHC must have a very high luminosity: the very short bunch crossing interval (25 ns, i.e., 40 MHz frequency) and the high number of bunches accelerated by the machine (2808 per beam) will allow to reach the peak luminosity of $10^{34}$ cm$^{-2}$s$^{-1} = 10$ nb$^{-1}$s$^{-1}$. The bunch structure is such that only about 80% of the bunches will be filled [12]. The luminosity delivered by LHC during the first three years will be of $\int L \, dt = 20$ fb$^{-1}$ per year or $L = 2 \times 10^{33}$ cm$^{-2}$s$^{-1}$, and later $\int L \, dt = 100$ fb$^{-1}$ per year or $L = 10^{34}$ cm$^{-2}$s$^{-1}$.

The parameters of the LHC are summarized in Table 1.1.

This design has the drawback that the total event rate becomes so high that several interactions overlap in the same bunch crossing (pile up). Given the total non-diffractive inelastic $p-p$ cross section of 55 mb predicted by PYTHIA, on average 17.3 events will occur at every bunch crossing. With about 50 charged tracks per interaction. The high bunch crossing frequency, the high event rate and the pile-up of several events in the same bunch crossing dictate strict requirements on the design of detectors. To cope with a bunch crossing rate of 25 ns and a pile-up of about 20 events per crossing, the detectors should have a very fast time response and the readout electronics should also be very fast. Due to the presence of pile-up, high granularity is also required to avoid
Table 1.1: LHC parameters for p–p and Pb–Pb collisions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>p–p</th>
<th>$^{208}$Pb$^{82+}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center-of-mass energy (TeV)</td>
<td>14</td>
<td>1148</td>
</tr>
<tr>
<td>Number of particles per bunch</td>
<td>$1.1 \times 10^{11}$</td>
<td>$\sim 8 \times 10^7$</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>2808</td>
<td>608</td>
</tr>
<tr>
<td>Design Luminosity (cm$^{-2}$s$^{-1}$)</td>
<td>$10^{34}$</td>
<td>$2 \times 10^{27}$</td>
</tr>
<tr>
<td>Luminosity lifetime (h)</td>
<td>10</td>
<td>4.2</td>
</tr>
<tr>
<td>Bunch length (mm)</td>
<td>53</td>
<td>75</td>
</tr>
<tr>
<td>Beam radius at interaction point (μm)</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>Time between collisions (ns)</td>
<td>24.95</td>
<td>124.75$\times 10^3$</td>
</tr>
<tr>
<td>Bunch crossing rate (MHz)</td>
<td>40.08</td>
<td>0.008</td>
</tr>
<tr>
<td>Circumference (km)</td>
<td>26.659</td>
<td></td>
</tr>
<tr>
<td>Dipole field (T)</td>
<td>8.3</td>
<td></td>
</tr>
</tbody>
</table>

the overlap of particles in the same sensitive elements. High granularity means a large number of electronics channels, and therefore high cost. LHC detectors will also have to stand an extremely high radiation dose; special radiation-hard electronics must be used. Additional requirements apply to the online trigger selection, that has to deal with a background rate several orders of magnitude higher than the signal rate.

Fig. 1.2 shows some of the cross sections and the production rate at LHC of interesting processes as a function of the center-of-mass energy and of the mass of the produced particle. In Table 1.2 the cross section and the number of events produced for a given process per experiment for low luminosity ($\mathcal{L} = 2 \times 10^{33}$ cm$^{-2}$s$^{-1}$) are reported. The Higgs cross section increases steeply with the center-of-mass energy, while the total cross section (i.e., the background) remains almost constant. Therefore the highest center-of-mass energy should be used. The idea behind the Large Hadron Collider is to reuse the existing 27 km long LEP tunnel to install a new p–p collider. Considerable financial savings are obtained from the fact that the tunnel and several infrastructures (including pre-accelerators) already exist. However, the size of the tunnel limits the center-of-mass energy to 14 TeV, since the beams must be bent by dipole magnets whose maximum field is currently limited at about 8 T.

One very remarkable aspect of LHC physics is the overwhelming background rate compared to the interesting physics processes: the Higgs production, for instance, has a cross section at least ten orders of magnitude smaller than the total inelastic cross section, as shown in Fig. 1.2. In fact, the bulk of the events produced in p–p collisions is either due to low-$p_T$ scattering, where the protons collide at large distances, or to QCD high-$p_T$ processes of the type:
1.1 Why LHC?

**Figure 1.2:** Cross section as a function of the center-of-mass energy (left) and rate of events at LHC as a function of the mass of the produced particle (right) for interesting processes.

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma$</th>
<th>Events/sec</th>
<th>Events/year</th>
<th>Other machine</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \rightarrow e\nu$</td>
<td>20 nb</td>
<td>15</td>
<td>$10^8$</td>
<td>$10^4$ LEP / $10^7$ Tevatron</td>
</tr>
<tr>
<td>$Z \rightarrow ee$</td>
<td>2 nb</td>
<td>1.5</td>
<td>$10^7$</td>
<td>$10^7$ LEP</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>1 nb</td>
<td>0.8</td>
<td>$10^7$</td>
<td>$10^5$ Tevatron</td>
</tr>
<tr>
<td>$b\bar{b}$</td>
<td>0.8 mb</td>
<td>$10^5$</td>
<td>$10^{12}$</td>
<td>$10^8$ Belle/BaBar</td>
</tr>
<tr>
<td>$\tilde{g}\tilde{g}$ (m = 1 TeV)</td>
<td>1 pb</td>
<td>0.001</td>
<td>$10^4$</td>
<td></td>
</tr>
<tr>
<td>$H$ (m = 0.8 TeV)</td>
<td>1 pb</td>
<td>0.001</td>
<td>$10^4$</td>
<td></td>
</tr>
<tr>
<td>$H$ (m = 0.2 TeV)</td>
<td>20 pb</td>
<td>0.01</td>
<td>$10^5$</td>
<td></td>
</tr>
</tbody>
</table>

**Table 1.2:** Expected cross sections and number of events per second and per year for one experiment at LHC.
All these events are collectively called “minimum bias” and in LHC studies are in general considered uninteresting since they constitute a background for other processes, where massive particles like the Higgs are created in the hard scattering. This classification is somewhat arbitrary; for example, this definition of minimum bias events includes $b \bar{b}$ production that is of interest for B-physics studies.

Another main characteristic of LHC is the span in energy of the initial state partons: in Fig. 1.3 the CTEQ4M Parton Distribution Functions (PDFs). [13] at two different values of $Q^2$ are shown. The fact that the two partons interact with unknown energies has two fundamental consequences. First of all the total energy of an event is unknown, because the proton remnants, that carry a sizable fraction of the proton energy, are scattered at small angles and are predominantly lost in the beam pipe, escaping undetected. Experimentally, it is therefore not possible to define the total and missing energy of the event, but only the total and missing transverse energies (in the plane transverse to the beams). Moreover, the center of mass may be boosted along the beam direction.

**Figure 1.3:** Parton density functions for $Q^2 = 20 \text{ GeV}/c^2$ and $Q^2 = 10^4 \text{ GeV}/c^2$. 
It is therefore very useful to use experimental quantities that are invariant under such boosts as the transverse momentum $p_T$. The *rapidity*, choosing the beam direction as $z$ axis, is defined as:

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$

(1.2)

and it is often used to describe angular distributions because it is additive under boosts along the $z$ direction, therefore the shape of $dN/dy$ distributions is invariant under such boosts. For ultra-relativistic particles ($p \gg m$) the rapidity is approximated by the *pseudorapidity*:

$$\eta = -\ln \tan \frac{\theta}{2}$$

(1.3)

where $\theta$ is the angle between the particle momentum and the $z$ axis. The pseudorapidity can be reconstructed just from the measurement of the $\theta$ angle and can be also used for particles for which the mass and momentum are not measured. Statistical particle distributions are flat in $\eta$ for many physics production models. For instance, the distribution of charged particles in the underlying event is flat in $\eta$ in the central region [14]. For this reason is often useful to define the cone around a given particle in terms of pseudorapidity:

$$\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$$

(1.4)

### 1.2 CMS Physics Program

Two general-purpose experiments are taking data at LHC: ATLAS (A Toroidal Lhc ApparatuS [15]) and CMS (Compact Muon Solenoid [16]). A B-physics dedicated experiment (LHCb [17]) is also in operation, it is devoted to study $b$-hadrons production at small angle at low luminosity. Finally, the LHC will also provide Pb-Pb collision with $\sqrt{s} = 1312$ TeV at a luminosity of $10^{29}$ cm$^{-2}$s$^{-1}$. The ALICE [18] experiment is dedicated to study these heavy ion collisions.

The main goals of the general purpose experiment CMS are:

- study the mechanism that breaks the symmetry of the SM Lagrangian giving rise to the particle masses.
  Within the SM this means to search for the Higgs boson from $m_H = 100$ GeV to $m_H = 1$ TeV. If the Higgs is found, understand if it is the SM Higgs or a SUSY Higgs; if the Higgs is not found, look for alternative models.

- search for new physics, especially if the Higgs is not found.
  Concerning supersymmetry, all the s-particles with mass $m_\tilde{s} \leq 3$ TeV will
be accessible. For exotic models (like lepto-quark, technicolor, new strong interaction, new lepton families, additional bosons, extra-dimensions) the mass reach is 5 TeV.

- perform precision measurements in the electroweak sector ($m_W$, $m_{top}$, triple gauge couplings, $\sin^2 \theta_W$), in QCD, and in the CP violation and B physics sector.

Concerning the precision electroweak measurements, it should be noted that, in order to have a comparable impact in the determination of the Higgs mass from the fit of the electroweak observables, the top mass and the W mass should be measured with a relative precision given by:

$$\Delta m_W = 0.7 \times 10^{-2} \Delta m_{top}$$

The target precision on these quantities will be $\Delta m_W \leq 15$ MeV and $\Delta m_{top} \leq 2$ GeV. These precisions will not be trivial to achieve being at a hadron collider where the initial state of the parton-parton collision is not well known and where the final state is complicated by the presence of many other particles produced.

The first years will be devoted to the Standard Model “re-discovery”, a series of standard processes will be searched to function as standard candles: Drell-Yan with the Z peak and quarkonia low mass resonances, W production and $t\bar{t}$ production. The analysis of these processes will allow to calibrate the detectors: the lepton energy scale can be kept under control exploiting the di-lepton mass resonances ($Z$, $J/\psi$ and $\Upsilon$), the missing transverse energy can be calibrated with the $W$ transverse mass, finally with the huge rate of $t\bar{t}$ we can calibrate jets and measure the $b$-tagging efficiency. Moreover some processes will be very useful at the beginning to tune the Monte Carlo SM description. $W/Z +$ jets are the largest backgrounds for many new physics searches therefore the inclusive $Z$ $p_T$ spectrum and the rate of events with different jet multiplicities will be measured from data. Analogously, the measure of the $W^+/W^-$ asymmetry will allow to increase the precision on the PDF.

Once the main experimental systematics will be under control and the Monte Carlo description of the SM at the LHC energy scale will be tuned from data, the conditions will have been established for any possible claim of new physics.

More detailed descriptions of the road to the discovery [19] and the physics program at CMS [20], [21] can be found elsewhere. As an introduction to the analysis presented in Chapter 5, a brief review of the Higgs physics at LHC is here reported.
1.2.1 Standard Model Higgs Boson Search

While the Higgs boson mass is not predicted by the theory, the Higgs boson couplings to the fermions and bosons are predicted to be roughly proportional to the corresponding particle masses. For this reason, the Higgs boson production and decay processes are dominated by channels involving the coupling of Higgs boson to heavy particles, mainly to $W^\pm$ and $Z$ bosons and to the third generation of fermions. For what concerns the remaining gauge bosons, the Higgs boson does not couple to photons and gluons at tree level, but only by one-loop graphs where the main contribution is given by $t$ loops for the $gg \rightarrow H$ channel and by $W^+W^-$ and $t$ loops for the $\gamma\gamma \rightarrow H$ channel.

1.2.1.1 Higgs Boson Production

The main processes contributing to the Higgs boson production at a hadron collider are represented by the Feynman diagrams in Fig. 1.4. The corresponding cross sections for a center of mass energy $\sqrt{s} = 14$ TeV, which is the design value at LHC, are shown in Fig. 1.5.

![Feynman diagrams](image-url)

**Figure 1.4:** Higgs boson production mechanisms at tree level in proton-proton collisions: (a) gluon-gluon fusion; (b) $VV$ fusion; (c) $W$ and $Z$ associated production (or Higgsstrahlung); (d) $t\bar{t}$ associated production.
Physics at the Large Hadron Collider (LHC)

\[ \sigma(pp\rightarrow H+X) [pb] \]
\[ \sqrt{s} = 14 \text{ TeV} \]
\[ M_t = 175 \text{ GeV} \]
CTEQ4M

Figure 1.5: Higgs boson production cross sections at $\sqrt{s} = 14$ TeV as a function of the Higgs boson mass. The cross sections are calculated using HIGLU and other programs [22]; they contain higher order corrections and the CTEQ6m [23] PDF has been adopted.

Gluon-gluon fusion The $gg$ fusion is the dominating mechanism for the Higgs boson production at the LHC over the whole Higgs boson mass spectrum. The process is shown in Fig. 1.4(a), with a $t$ quark-loop as the main contribution.

The cross section for the basic gluon to Higgs boson process is [24]

\[ \sigma(gg \rightarrow H) = \frac{G\alpha_s^2(\mu_R^2)}{288\sqrt{2\pi}} \left( \frac{3}{4} \sum_q A_{1/2}^H(\tau_Q) \right)^2, \quad (1.6) \]

where $A_{1/2}^H(\tau_Q)$ with $\tau_Q = M_H^2/4m_q^2$ is a form factor [25] normalized so that $A_{1/2}^H(\tau_Q) \rightarrow 4/3$ for $\tau_Q \rightarrow 0$.

The lowest order cross section has large corrections from higher order QCD diagrams. The increase in cross section from higher order diagrams is conventionally defined as the $K$-factor:

\[ K = \frac{\sigma_{NLO}}{\sigma_{LO}} \quad (1.7) \]

where LO (NLO) refer to leading (next-to-leading) order results. The NLO QCD corrections to the top and bottom quark loops [26, 27, 28] result in a 50 to 100% increase of the cross section.
In the limit of very heavy top quarks the NNLO QCD corrections have been recently calculated \cite{29,30,31} increasing the total cross section further by \( \sim 20\% \). A full massive NNLO calculation is not available but the approximate NNLO results have been improved by a soft-gluon resummation at the next-to-next-to-leading log (NNLL) level, which yields another increase of the total cross section by about 10\% \cite{32}.

Electroweak corrections have been computed and turn out to be small \cite{33,34,35,36}. The theoretical uncertainties of the total cross section can be estimated as 20\% at NNLO due to the residual scale dependence, the uncertainties of the parton densities and due to neglected quark mass effects.

The production of the Higgs boson through gluon fusion is sensitive to a fourth generation of quarks. Because the Higgs boson couples proportionally to the fermion mass, including a fourth generation of very heavy quarks will more than double the cross section.

**Vector boson fusion**  The \( VV \) fusion (Fig. 1.4(b)) is the second contribution to the Higgs boson production cross section. It is about one order of magnitude lower than \( gg \) fusion for a large range of \( M_H \) values and the two processes become comparable only for very high Higgs boson masses \( \mathcal{O}(1 \text{ TeV}) \). However, this channel is very interesting because of its clear experimental signature: the presence of two spectator jets with high invariant mass in the forward region provides a powerful tool to tag the signal events and discriminate the backgrounds, thus improving the signal to background ratio, despite the low cross section. Moreover, both leading order and next-to-leading order cross sections for this process are known with small uncertainties and the higher order QCD corrections are quite small.

**Associated production**  In the \textit{Higgsstrahlung} process (Fig. 1.4(c)), the Higgs boson is produced in association with a \( W^\pm \) or \( Z \) boson, which can be used to tag the event. The cross section for this process is several orders of magnitude lower than \( gg \) and \( VV \) fusion ones. The QCD corrections are quite large and the next-to-leading order cross section is increased by a factor of \( 1.2 \div 1.4 \) relative to the leading order one.

The last process, illustrated in Fig. 1.4(d), is the associated production of a Higgs boson with a \( t\bar{t} \) pair. Also the cross section for this process is several orders of magnitude lower than those of \( gg \) and \( VV \) fusion, but the presence of the \( t\bar{t} \) pair in the final state can provide a good experimental signature. The higher order corrections increase the cross section by a factor of about 1.2.
1.2.1.2 Higgs Boson Decay

The branching ratios of the different Higgs boson decay channels are shown in Fig. 1.6 as a function of the Higgs boson mass. Fermionic decay modes dominate the branching ratio in the low mass region (up to $\sim 150$ GeV). In particular, the channel $H \rightarrow b\bar{b}$ has the highest branching ratio since the $b$ quark is the heaviest fermion available. When the decay channels into vector boson pairs open up, they quickly dominate. A peak in the $H \rightarrow W^+W^-$ decay is visible around 160 GeV, when the production of two on-shell $W$'s becomes possible and the production of a real $ZZ$ pair is still not allowed. At high masses ($\sim 350$ GeV), also $t\bar{t}$ pairs can be produced.

![Branching Ratios for Higgs Boson Decay Channels](image)

**Figure 1.6:** Branching ratios for different Higgs boson decay channels as a function of the Higgs boson mass. They are calculated with the program HDECAY [37] which includes the dominant higher order corrections to the decay width.

As shown in Fig. 1.6, the branching ratios change dramatically across the possible range of the Higgs boson mass requiring different strategies for the different Higgs boson mass range. The most promising decay channels for the Higgs boson discovery do not only depend on the corresponding branching ratios, but also on the capability of experimentally detecting the signal and rejecting the backgrounds. Fully hadronic events are the most copious final states from Higgs boson decays. These decays can not be easily resolved when merged in QCD background, therefore topologies with leptons or photons are preferred, even if they have smaller branching ratio.
Such channels are illustrated in the following, depending on the Higgs boson mass range.

**Low mass region** Though the branching ratio in this region is dominated by the Higgs boson decay into $b\bar{b}$, the background constituted by the di-jet production (more than six order of magnitude higher than the signal) makes quite difficult to use this channel for a Higgs boson discovery. Some results from this channel can be obtained when the Higgs boson is produced in association with a $t\bar{t}$ or via *Higgsstrahlung*, since in this case the event has a cleaner signature, despite its low cross section.

The most promising way of identifying a Higgs boson in the low mass region is to select the decay channel $H \rightarrow \gamma\gamma$. In spite of its lower branching ratio (around $10^{-3}$), the two high energy photons constitute a very clear signature, which only suffers from the $q\bar{q} \rightarrow \gamma\gamma$ and $Z \rightarrow e^+e^-$ backgrounds or jets faking photons. The expected signal to background ratio is $10^{-2}$, which make this channel much more attractive than the $b\bar{b}$ channel.

**Intermediate mass region** For a mass value $130 \text{ GeV} \leq M_H \leq 2M_Z$, the Higgs boson decays into $WW^{(*)}$ and $ZZ^*$ open up and their branching ratios quickly increase. Thus the best channels in this mass region are $H \rightarrow WW^{(*)} \rightarrow 2\ell2\nu$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ with only one vector boson on-shell.

The branching ratio of $H \rightarrow WW^{(*)}$ is higher, because of the higher coupling of the Higgs boson to charged current with respect to neutral current. Moreover, this decay mode becomes particularly important in the mass region between $2M_W$ and $2M_Z$, where the Higgs boson can decay into two real $W$'s (and not yet into two real $Z$'s): its branching ratio is $\sim 1$. Anyway, in such channel because of the presence of the two $\nu$'s in the final state, the Higgs boson mass cannot be reconstructed. Such measurement can be performed instead when one $W$ decays leptonically and the other one decays in two quarks. But, in this case, the final state suffers from the high hadronic background.

The decay $H \rightarrow ZZ^* \rightarrow 4\ell$, despite its lower branching ratio, offers a very clear experimental signature and high signal to background ratio. Furthermore, it allows to reconstruct the Higgs boson mass with high precision.

**High mass region** This region corresponds to Higgs boson mass values above the $2M_Z$ threshold, where the Higgs boson can decay into a real $ZZ$ pair. Though the $H \rightarrow ZZ$ width is still lower than $H \rightarrow WW$ one, a decay into four charged leptons (muons or electrons) is surely the “golden channel” for a high mass Higgs boson discovery.

The upper mass limit for detecting the Higgs boson in this decay channel is given by the reduced production rate and the increased width of the Higgs
boson. As an example, less than 200 Higgs particles with $M_H = 700$ GeV will decay in the $H \rightarrow ZZ \rightarrow 4\ell$ channel in a year at high luminosity and the large width will increase the difficulty to observe the mass peak.

In order to increase the sensitivity to a heavy Higgs boson production, decay channels with one boson decaying into jets or neutrinos can be also considered. The decay channel $H \rightarrow WW \rightarrow \ell\ell\nu\nu j j$, where $j$ denotes a jet from a quark in the $W$ decay, has a branching ratio just below 30%, yielding a rate about 50 times higher than the four lepton channel from $H \rightarrow ZZ$ decays. The decay channel $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu\bar{\nu}$ which has a six times larger branching ratio than the four lepton channel could also be interesting as shown in Chapter 5.

1.2.1.3 Higgs Boson Total Decay Width

The total width of the Higgs boson resonance is shown in Fig. 1.7 as a function of the Higgs mass. Below the $2M_W$ threshold, the Higgs boson width is of the order of the MeV, then it rapidly increases, but remains lower than 1 GeV up to $M_H \sim 200$ GeV: the low mass range is therefore the most challenging region, because the Higgs boson width is dominated by the experimental resolution.

![Figure 1.7: Higgs boson total decay width as a function of the Higgs boson mass.](image)

In the high mass region ($M_H \geq 2M_Z$), the total Higgs boson width is dominated by the $W^+W^-$ and $ZZ$ partial widths, which can be written as follows:

$$\Gamma(H \rightarrow W^+W^-) = \frac{g^2}{64\pi} \frac{M_H^3}{M_W^2} \sqrt{1-x_W} \left(1 - x_W + \frac{3}{4}x_W^2\right)$$  (1.8)
\[ \Gamma(H \to ZZ) = \frac{g^2}{128\pi} \frac{M_H^3}{M_W^2} \sqrt{1 - x_Z^2} \left( 1 - x_Z^2 + \frac{3}{4} x_Z^2 \right) \]  
\text{(1.9)}

where
\[ x_W = \frac{4M_W^2}{M_H^2}, \quad x_W = \frac{4M_Z^2}{M_H^2}. \]

As the Higgs boson mass grows, \( x_W, x_Z \to 0 \) and the leading term in eqs. 1.8 and 1.9 grows proportional to \( M_H^3 \). Summing over the \( W^+W^- \) and \( ZZ \) channels, the Higgs boson width in the high mass region can be written as
\[ \Gamma(H \to VV) = \frac{3}{32\pi} \frac{M_H^3}{v^2}. \]  
\text{(1.10)}

From eq. 1.10, it results that \( \Gamma_H \sim M_H \) for \( M_H \sim 1 \text{ TeV} \). When \( M_H \) becomes larger than a TeV, therefore, it becomes experimentally very problematic to separate the Higgs boson resonance from the \( VV \) continuum. Actually, being the resonance width larger than its own mass, the Higgs boson cannot be properly considered as a particle any more. In addition, if the Higgs boson mass is above 1 TeV, the SM predictions violate unitarity. All these considerations suggest the TeV as a limit to the Higgs boson mass: at the TeV scale at least, the Higgs boson must be observed, or new physics must emerge.

### 1.3 The CMS Detector

CMS implement a general purpose structure driven by the configuration of the magnetic field. The chosen magnetic field intend to maximize the \( BL^2 \) term determining the resolution on the measurement of the momentum of the muon. Good resolution for muons from few GeV up to 1 TeV are mandatory to fulfill the physics program.

The size of the experiment is determined mainly by the fact that it is designed to identify and measure the energy and momentum of most of the very energetic particles emerging from the \( p-p \) collision. The interesting particles are produced over a wide range of energy (from few hundreds of MeV to a few TeV) and over the full solid angle. No particle of interest should escape unseen. This means that the two experiments should avoid any cracks in the acceptance.

CMS has adopted a compact layout with a solenoid with a very intense field \( B = 4 \text{ T} \) and moderate dimensions \( R = 3 \text{ m} \). The calorimeters are inside the field. The main technological challenge for CMS is to reach this high and uniform value of the \( B \) field over such a large volume.

A detailed description of CMS can be found in [38], the main features of the CMS sub-detectors are listed in the following. In Chapter 2 more details about the sub-detectors for muon identification and tracking are also reported.
The CMS tracker is inside the 4 T magnetic field and it is made entirely of silicon sensors (pixels and strips). The resolution on the charged particle momentum is \( \sigma_{p_T}/p_T \sim 1.5 \times 10^{-4} p_T \oplus 0.005 \). The outer radius of the tracking detector is \( \sim 110 \text{ cm} \).

CMS has an homogeneous calorimeter made of PbWO\(_4\) crystals. A typical energy resolution, measured with electron beams having momenta between 20 and 250 GeV and limited to a 4 \( \times \) 4 mm\(^2\) region around the point of maximum containment of the tested supermodule, was

\[
\left( \frac{\sigma}{E} \right)^2 = \left( \frac{2.8\%}{\sqrt{E}} \right)^2 + \left( \frac{0.12}{E} \right)^2 + (0.30\%)^2, \quad (1.11)
\]

where \( E \) is in GeV.

The CMS hadronic calorimeter is made of Cu-scintillator with an energy resolution of

\[
\frac{\sigma_E}{E} \sim \frac{100\%}{\sqrt{E}} \oplus 0.05, \quad (1.12)
\]

where \( E \) is in GeV. Due to the constraint of going into the magnet, the calorimeter is not long enough to contain the full hadronic shower (\( \sim 10 \lambda_T \)). Thus an additional tail catcher (the HO detector - a layer of...
scintillators) has been placed after the calorimeter in order to limit the punch through into the muon system.

- Finally muons are very robust, clean and unambiguous signature of much of the physics that CMS was designed to study. The ability to trigger and reconstruct muons at the highest luminosities of the LHC was incorporated into the design of the detector. The choice of the magnet, as already said, was motivated by the necessity to measure TeV muons. In CMS the muon chambers are placed in the iron of the magnet yoke and the muon transverse momentum resolution is $\sigma_{p_T}/p_T \sim 5\%$ at 1 TeV.
Chapter 2

Muon Detection in the CMS Detector

2.1 Detectors for Muons

An efficient, clean and precise muon detection is a key feature of CMS: the detectors dedicated to the muon identification, trigger and reconstruction are mainly the inner tracker [39] and the muon system [40] which is instrumented with three different, stand-alone and independent sub-detectors: Drift Tubes in the barrel, Cathode Strip Chambers in the endcaps and Resistive Plate Chambers in both regions. Finally, precise muon tracking is made possible by the very high magnetic field delivered by the solenoid [41].

2.1.1 Inner Tracking System

The inner tracking system of CMS is designed to provide a precise and efficient measurement of the trajectories of charged particles as well as a precise reconstruction of secondary vertices. It surrounds the interaction point and has a length of 5.8 m and a diameter of 2.5 m. At the LHC design luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$ there will be on average about 1000 particles, from about 20 overlapping proton-proton interactions, traversing the tracker for each bunch crossing, i.e. every 25 ns. Therefore a detector technology ensuring high granularity and fast response is required. These features imply a high power density of the on-detector electronics which in turn requires efficient cooling (it is foreseen that the whole tracker volume will be operated at, or slightly below, -10 °C). This is in direct conflict with the aim of keeping to the minimum the amount of material in order to limit multiple scattering, bremsstrahlung, photon conversion and nuclear interactions. Figure 2.1 shows the material budget of the
CMS tracker in units of radiation length. It increases from 0.4 $X_0$ at $\eta \sim 0$ to about 1.8 $X_0$ at $|\eta| \sim 1.4$, beyond which it falls to about 1 $X_0$ at $|\eta| \sim 2.5$.

Figure 2.1: Tracker material budget in units of radiation length as a function of pseudorapidity for the different subdetectors (left) and broken down into the functional contributions (right).

In order to keep the occupancy at or below 1%, pixelated detectors have to be used at radii below 10 cm. For a pixel size of $100 \times 150 \mu m^2$ in $r$-$\phi$ and $z$, respectively, which is driven by the desired impact parameter resolution, the occupancy is of the order $10^{-4}$ per pixel and LHC bunch crossing (i.e., 4 Hz per pixel). At intermediate radii ($20 \text{ cm} < r < 55 \text{ cm}$) the reduced particle flux allows the use of silicon micro-strip detectors with a typical cell size of $10 \text{ cm} \times 80 \mu m$, leading to an occupancy of up to 2-3% per strip and LHC bunch crossing (i.e., $\sim 1 \text{ kHz}$ per strip). In the outer region ($55 \text{ cm} < r < 110 \text{ cm}$) the strip pitch can be further increased.

A schematic drawing of the CMS tracker is shown in Fig. 2.2. At radii of 4.4, 7.3 and 10.2 cm, three cylindrical layers of hybrid pixel detector modules surround the interaction point. They are complemented by two disks of pixel modules on each side. The pixel detector delivers three high precision space points on each charged particle trajectory. In total the pixel detector covers an area of about 1 m$^2$ and has 66 million pixels.

The radial region between 20 cm and 116 cm is occupied by the silicon strip tracker. It is composed of three different subsystems. The Tracker Inner Barrel and Disks (TIB/TID) extend in radius toward 55 cm and are composed of 4 barrel layers, supplemented by 3 disks at each end. TIB/TID deliver up to 4 $r$-$\phi$ measurements on a trajectory. Their strips are parallel to the beam axis.
in the barrel and radial on the disks. The single point resolution in TIB is 23 \( \mu m \) in the two inner layers and 35 \( \mu m \) in the two outer layers. The TIB/TID is surrounded by the Tracker Outer Barrel (TOB). It has an outer radius of 116 cm and consists of 6 barrel layers. It provides other 6 \( r-\phi \) measurements with single point resolution of 53 \( \mu m \) in the inner four layers and 35 \( \mu m \) in the outer two layers. The TOB extends in \( z \) between \pm 118 cm. Beyond this \( z \) range the Tracker EndCaps (TEC+ and TEC- where the sign indicates the location along the \( z \) axis) cover the region \( 124 \text{ cm} < |z| < 282 \text{ cm} \) and \( 22.5 \text{ cm} < r < 113.5 \text{ cm} \). Each TEC is composed of 9 disks, carrying up to 7 rings of silicon micro-strip detectors with radial strips. Thus, they provide up to 9 \( r-\phi \) measurements per trajectory.

In addition, the modules in the first two layers and rings, respectively, of TIB, TID and TOB as well as rings 1, 2, and 5 of the TECs carry a second micro-strip detector module which is mounted back-to-back with a stereo angle of 100 mrad in order to provide a measurement of the second co-ordinate (\( z \) in the barrel and \( r \) on the disks). The achieved single point resolution of this measurement is 230 \( \mu m^2 \) and 530 \( \mu m^2 \) in TIB and TOB, respectively, and varies with pitch in TID and TEC. This tracker layout ensures at least \( \sim 9 \) hits in the silicon strip tracker in the full range of \( |\eta| < 2.4 \) with at least \( \sim 4 \) of them being two-dimensional measurements, as shown in Fig. 2.3. The ultimate acceptance of the tracker ends at \( |\eta| \sim 2.5 \). The CMS silicon strip tracker has a total of 9.3 million strips and 198 m\(^2\) of active silicon area.
2.1.2 Muon System

As implied by the experiment’s middle name, the detection of muons is of central importance to CMS, being a powerful tool to recognize signatures of interesting processes over the very high QCD background rate expected at LHC with full luminosity. The detection of narrow states decaying into muons over a wide range of masses will pose stringent requirements on the momentum resolution: the goal is to reach $\Delta p_T/p_T \sim 10\%$ at $p_T = 1$ TeV.

The muon system has 3 functions: muon identification, momentum measurement and triggering. Good muon momentum resolution is enabled by the high magnetic field while the big amount of material and the flux-return yoke serves as hadron absorber for the identification of muons. The material thickness crossed by muons, as a function of pseudorapidity, is shown in Fig. 2.4: negligible punchthrough reaches the system because the amount of material in front of the muon system exceeds 16 interaction lengths.

The muon system has a cylindrical, barrel section and 2 planar endcap regions (see Figures 2.5 and 2.6 for a schematic view of the muon system). With this geometrical layout the muon detector elements cover the full pseudorapidity interval $|\eta| < 2.4$ with no acceptance gaps, muon identification is ensured over the range $10^\circ < \theta < 170^\circ$.

In the barrel region, where the neutron-induced background is small, the muon rate is low and the magnetic field is uniform and mostly contained in the steel yoke, drift chambers with standard rectangular drift cells are used. The barrel drift tube (DT) chambers cover the pseudorapidity region $|\eta| < 1.2$ and
Figure 2.4: Material thickness in radiation lengths (above) and interaction lengths (below) after the ECAL, HCAL, and at the depth of each muon station as a function of pseudorapidity. The thickness of the forward calorimeter (HF) remains approximately constant over the range $3 < |\eta| < 5$ (not shown).
Figure 2.5: Longitudinal view of one quarter of the CMS detector.

Figure 2.6: Transverse view of the barrel region of the CMS detector. Barrel wheels are numbered over the z direction (-2, -1, 0, 1, 2).
are organized into 4 stations interspersed among the layers of the flux return plates.

In the 2 endcap regions of CMS, where the muon rates and background levels are high and the magnetic field is large and non-uniform, the muon system uses cathode strip chambers (CSC). With their fast response time, fine segmentation, and radiation resistance, the CSC’s identify muons between $|\eta|$ values of 0.9 and 2.4. There are 4 CSC stations in each endcap, with chambers positioned perpendicular to the beam line and interspersed between the flux return plates. The cathode strips of each chamber run radially outward and provide a precision measurement in the $r\phi$ bending plane. The anode wires run approximately perpendicular to the strips and are also read out in order to provide measurements of $\eta$ and the beam-crossing time of a muon.

A crucial characteristic of the DT and CSC subsystems is that they can each trigger on the muon $p_T$ with good efficiency and high background rejection, independently of the rest of the detector. The Level-1 trigger $p_T$ resolution is about 15% in the barrel and 25% in the endcap.

Because of the uncertainty in the background rates and in the ability of the muon system to measure the correct beam-crossing time when the LHC reaches full luminosity, a complementary, dedicated trigger system consisting of Resistive Plate Chambers (RPC) was added in both barrel and endcap regions. The RPC’s provide a fast, independent, and highly-segmented trigger with a sharp $p_T$ threshold over a large portion of the rapidity range ($|\eta| < 1.6$) of the muon system. They produce a fast response with good time resolution but coarser position resolution than the DT’s or CSC’s.

A total of 6 layers of RPC’s are embedded in the barrel muon system, 2 in each of the first 2 stations, and 1 in each of the last 2 stations. The redundancy in the first 2 stations allows the trigger algorithm to work even for low-$p_T$ tracks that may stop before reaching the outer 2 stations. In the endcap region, there is a plane of RPC’s in each of the first 3 stations.

Finally, a sophisticated alignment system measures the positions of the muon detectors with respect to each other and to the inner tracker, in order to optimize the muon momentum resolution.

### 2.1.2.1 Drift Tube Chambers

The central region of the muon detector, instrumented with the DT chambers, has a primary importance for the CMS physics program: the hadronic activity due to pile-up tends to be in the forward-backward regions, while the interesting physics processes are characterized by hard scattering with large center of mass energy and not too high longitudinal boost, hence the produced particles tend to go in the central region.
A detailed description of the DT detector is reported here as an introduction to Chapter 3, where the DT calibration and reconstruction algorithms will be presented and their performance on simulated bunched data and real cosmic data will be shown.

**Chamber design** A DT chamber is shown in Fig. 2.7, it is made of 3 (or 2) superlayers (SL’s) each made of 4 layers of rectangular drift cells staggered by half a cell. Each SL provides the measurement of a two-dimensional segment solving the left-right ambiguity of a single layer by means of pattern recognition. The wires in the 2 outer SL’s are parallel to the beam line and provide a track measurement in the magnetic bending plane ($r$-$\phi$). In the inner SL, the wires are orthogonal to the beam line and measure the z position along the beam. This third, z-measuring, SL is not present in the fourth station, which therefore measures only the $r$-$\phi$ coordinate. The SL’s are glued to the outer faces of a honeycomb spacer which increases the lever arm between the two external SL’s, improving the $r$-$\phi$ track segment resolution within a station.

![Schematic view of a MB1/MB2 DT chamber. The two RPC’s of the muon station are also shown.](image)

Each single cell has a cross section of $13 \times 42 \text{ mm}^2$. The transverse dimension corresponds to a maximum drift time of 380 ns (i.e., 15 BX) in a gas mixture of 85% Ar + 15% CO$_2$. This value is small enough to produce a negligible occupancy and to avoid the need for multi-hit electronics, yet the cell is large enough to limit the number of active channels to an affordable value (172000 sensitive wires). A tube was chosen as the basic drift unit to obtain protection against damage from a broken wire and to partially decouple contiguous
2.1 Detectors for Muons

cells from the electromagnetic debris accompanying the muon. The wire length varies, depending on the SL type and on the station, from about 2 m to 3 m.

The goal of the mechanical precision of the chamber construction was to achieve a global resolution in $r$-$\phi$ of 100 $\mu$m. This figure makes the precision of the MB1 chamber (the innermost layer) comparable to the multiple scattering contribution up to $p_T = 200$ GeV. The 100 $\mu$m target chamber resolution is achieved by the 8 track points measured in the two $r$-$\phi$ SL's, the single wire resolution being better than 250 $\mu$m. To perform an efficient and precise BX assignment the deviation from linearity of the space-time relation in each drift cell must be less than 100-150 $\mu$m. A multi-electrode design (1 anode wire, 2 field shaping strips, and 2 cathode strips) ensures this performance also in the regions with stray magnetic field. The voltages applied to the electrodes are +3600V for wires, +1800V for strips, and -1200V for cathodes. See Fig. 2.8 for a sketch of the cell.

![Figure 2.8: Section of a drift tube cell showing drift lines and isochrones.](image)

**Read-out and Trigger Electronics** The Level-1 local trigger and read-out electronics is placed on the chamber, in a Mini-Crate (MC) mounted on the side opposite to the HV supply of each chamber.

Concerning the read-out devices, the MC is instrumented with Read-Out Boards (ROB), each equipped with four 32-channel High Performance Time to Digital Converters (HPTDC) [42]. There are five to seven of such ROB’s in each MC depending on the chamber size; the number of read-out channels varies from 608 to 800 per chamber.

The Level-1 Local Trigger reconstructs segments at the chamber level. The DT trigger front-end [43] is called Bunch and Track Identifier (BTI). It is directly connected to the read-out electronics, and performs a straight segment fit within a SL using at least three hits out of the four layers of drift cells. Aligned hits are recognized exploiting a generalization of the meantimer technique [44], which also returns the bunch crossing originating the segment. In $r$-$z$ SLs,
only segments pointing to the interaction point are selected. The segments reconstructed in the two \( r-\phi \) superlayers of each chamber are matched by the Track Correlator (TRACO), that improves the angular resolution thanks to the bigger lever arm. The Trigger Server (TS) selects, among all segment pairs in a chamber, the two corresponding to the highest \( p_T \) (i.e., with the smallest angular distance with respect to the radial direction to the vertex) and forwards them to the Drift Tube Track Finder (DTTF).

The DTTF performs the Regional Level-1 reconstruction: it matches the segments reconstructed in the four stations into muon track candidates, assigning the track parameters \( p_T, \eta, \phi \) and a quality word. This device, located in the underground control room, is based on precomputed, memory-resident Look-Up Tables (LUT). Finally, the candidates are sorted, and the four highest \( p_T \) muon candidates are delivered to the Global Muon Trigger.

2.1.3 Magnetic Field

The superconducting magnet of CMS has been designed to reach a 4 T field in a free volume of 6 m diameter and 12.5 m length with a stored energy of 2.7 GJ at full current. The ratio between stored energy and cold mass is high (11.6 KJ/kg), causing a large mechanical deformation (0.15%) during energizing, well beyond the values of previous solenoidal detector magnets. The parameters of the magnet are given in Table 2.1.

Table 2.1: Parameters of the CMS superconducting solenoid.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field</td>
<td>4 T</td>
</tr>
<tr>
<td>Field in the yoke</td>
<td>2 T</td>
</tr>
<tr>
<td>Inner Bore</td>
<td>5.9 m</td>
</tr>
<tr>
<td>Length</td>
<td>12.9 m</td>
</tr>
<tr>
<td>Number of Turns</td>
<td>2168</td>
</tr>
<tr>
<td>Current</td>
<td>19.5 kA</td>
</tr>
<tr>
<td>Stored energy</td>
<td>2.7 GJ</td>
</tr>
<tr>
<td>Hoop stress</td>
<td>64 atm</td>
</tr>
</tbody>
</table>

The flux is returned through a 10000 t yoke comprising 5 wheels and 2 endcaps, composed of 3 disks each. All these elements have been assembled with an alignment accuracy of 2 mm with respect to the ideal axis of the coil.

Fig. 2.9 shows the CMS magnetic field map.

The high field of the solenoid is the key to the very good momentum resolution of the CMS tracking detectors and, at the same time, the field confines some
fraction of the low momentum particles to the beam pipe region so that they do not confuse the inner tracking. On the other side the field sets the environment in which the detectors operate. The tracking and calorimetry subsystems are completely enclosed within the field, therefore the on-detector electronics has to be resistant to the magnetic field and the mechanical structures must tolerate the stress due to the magnetic force. The muon stations are interleaved in the flux return region with the iron plates of the yoke, therefore the structure in which the chambers are mounted cannot be regarded as fixed, so that alignment is an on-going process.

The full 4 T field is present in the region in which the innermost endcap CSC’s, the ME1/1 chambers, must operate. However, the field at this position is uniform and almost entirely axial, so that a proper wire tilt can partially compensate for the effect of the field on the drift of the electrons. At the next endcap station, ME1/2, the field has fallen off to a considerable degree, but it is no longer uniform and neither axial, as shown in Fig. 2.10. The radial component is the same as or greater than the axial component. Due to the large variation across the chamber, simple compensation schemes will not work. However, since the drift space in the CSC is small, the deterioration of resolution from the changing field components is also small, and the resolution of uncompensated chambers is within the requirements of the system.

In the barrel region most of the flux is contained within the iron plates of the yoke where the axial component of the field reaches ~ 1.8 T. The space where the DT chambers are placed should ideally be field-free. However in the iron gaps and at the end of the coil the residual magnetic field is far from being negligible. The axial and the radial components are shown in Fig. 2.11 for the various barrel DT stations. There are spatially limited regions where the field

Figure 2.9: Map of the CMS magnetic field.
in the radial direction can reach 0.8 T. In Chapter 3 the effect of the magnetic field on the electron drift velocity will be discussed.

While most of the magnetic flux is returned via the iron plates, the fringe field outside the detector remains uncomfortably large. In Fig. 2.12 we show the calculated field outside the solenoid in the $z = 0$ plane out to a radius of 50 m. In the region of $R = 4$-7 meters, the three cylindrical rings of iron plates are clearly visible, with a B field near saturation ($\sim 1.6$ T). Outside the detector, at a radius of 8-9 m, where electronics will be located, the field is roughly 0.05 T (500 gauss). At larger distances of 35 m (roughly the location of the underground control room) the field is still 0.0005 T (5 gauss). Consequently we will require careful shielding of the electronics throughout the CMS underground hall.

### 2.2 Muon Trigger

Physics at LHC begins online. The bunch crossing frequency at CMS interaction point is 40 MHz while technical difficulties in handling, storing and processing extremely large amounts of data impose a limit of about 100 Hz on the rate of events that can be written to permanent storage, as the average event size will be of about 1 MB.
2.2 Muon Trigger

Figure 2.11: Radial ($B_r$, left) and axial ($B_z$, right) components of the magnetic field in the different DT barrel stations as a function of the distance from the CMS center in the axial direction (along the $z$-axis). The shaded areas are the gaps between the detector wheels.

Figure 2.12: Magnetic field moving out radially from the beam line in the $z = 0$ plane. A non-negligible field exists at considerable distance from the detector.
The goal of the trigger is to perform the required huge on-line selection. This task is difficult not only because of the large rejection factor it requires but also because the output rate is already saturated by processes like $Z\rightarrow\ell\ell$ and $W\rightarrow\ell\nu$, where high-$p_T$ leptons are produced. The trigger must therefore be able to select events on the basis of their physics content, and online selection algorithms must have a level of sophistication comparable to that of offline reconstruction.

The time available to accept or reject an event is extremely limited, being the bunch crossing time of 25 ns, a time interval too small even to read out all raw data from the detector. For this reason CMS adopts a multi-level trigger design, where each step of the selection uses only part of the available data. In this way higher trigger levels have to process fewer events and have more time available, so they can analyze the events in full details using more refined algorithms.

The CMS trigger design is made of two physical steps, namely the Level-1 Trigger [45] and the High-Level Trigger (HLT) [46]. The first analyzes each 25-ns bunch crossing within a latency of 3 $\mu$s, whereas the second can operate on longer timescales, but always consistent with the overall Level-1 output rate. The Level-1 trigger is built of mostly custom-made hardware and it analyzes the detector information in a fairly coarse-grained scale. The CMS HLT system is software implemented in a single processor farm (referred to as “Event Filter Farm”). The HLT selection is implemented as a sequence of reconstruction and selection steps of increasing complexity, reconstruction refinement and physics sophistication. The fully programmable nature of the processors in the Event Filter Farm enables the implementation of very complex algorithms utilizing all the information in the event.

A detailed description of the performances of the CMS trigger system can be found in [47]. In the following only the main features of the muon trigger system are reported.

All the three muon subsystems (DT, CSC and RPC) have independent trigger capabilities and their overlap ensures high efficiency and redundancy over most of the muon spectrometer coverage.

### 2.2.1 Level-1 Trigger

The Level-1 muon trigger provides a fast estimate of the muon transverse momentum via look-up tables. The DT and CSC triggers determine the muon $p_T$ from the difference between segment slopes in successive layers of the muon spectrometer, whereas the RPC trigger compares the observed muon trajectory with predefined hit patterns as a function of $p_T$. All these triggers assume that muons are produced in a region around the LHC beam spot.
The Global Muon Trigger system is responsible for matching DT and CSC candidates with RPC candidates, as well as for rejecting unconfirmed candidates of low quality. Up to four muon candidates satisfying some minimal quality criteria and with the highest $p_T$ are forwarded to the HLT for further processing. The two main Level-1 muon triggers are the single-muon and double-muon triggers. The type of events contributing to the Level-1 muon trigger rate depends on the $p_T$ threshold used. Pion and kaon decays dominate in the region $p_T \approx 5$ GeV (although the probability of decays in the volume in front of the calorimeter is small, the number of hadrons is very high). Leptons from $b$ and $c$-quark decays dominate in the $5$ GeV $< p_T < 35$ GeV range, whereas at higher $p_T$ values $W \rightarrow \mu\nu$ events are the main component. At a luminosity of $10^{32}$ cm$^{-2}$ s$^{-1}$, the Level-1 single-muon rate is about 1 kHz for thresholds as low as 7 GeV while the di-muon rate is smaller than 200 Hz at the lowest useful threshold of 3 GeV.

The efficiency times acceptance of the Level-1 single-muon criteria on a $W \rightarrow \mu\nu$ sample generated in the fiducial volume $|\eta| < 2.4$ with $p_T > 10$ GeV is 83%. The combined efficiency of single and double-muon criteria on a $Z \rightarrow \mu\mu$ sample in a similar fiducial volume is 99%.

2.2.2 HLT Algorithms

In the first step of the HLT muon selection, referred to as Level-2, Level-1 muon candidates are used to seed the reconstruction of tracks in the muon chambers. A Level-2 $p_T$ threshold is applied and then the Level-3 reconstruction is carried out by combining Level-2 muons and charged-particle tracks reconstructed in the central tracker. The final filtering step is applied on the precisely measured Level-3 muons. Isolation requirements can be also applied using calorimeter information at Level-2 and tracker information at Level-3.

**Level-2 Reconstruction** The Level-2 reconstruction is based on Kalman-filter techniques and starts with an estimation of the seed state using the Level-1 information. The track parameters are propagated taking into account the multiple scattering and the energy losses due to ionization and bremsstrahlung in the muon chambers and in the return yoke. These material effects are estimated from fast parameterizations, avoiding time-consuming accesses to the detailed material and geometry descriptions. The required precision is obtained by using smaller steps in regions with larger magnetic field inhomogeneities.

**Level-3 Reconstruction** The track parameters of the Level-2 muon, constrained to the interaction region, define a $\eta - \phi$ rectangular region in the silicon tracker. Level-3 reconstruction starts from seeds in this Region Of Interest.
Muon Detection in the CMS Detector

A relaxed beam-spot constraint is applied to track candidates above a given transverse momentum threshold to obtain initial trajectory parameters. Trajectories are then grown using Kalman-filter techniques.

Isolation Isolation variables are defined as sums of transverse energies in the calorimeter towers (for Level-2) or of transverse momenta of charged-particle tracks (for Level-3) found in a cone around the direction of the muon. In the Level-2 isolation the calorimetric deposits are calculated as a weighted sum of the energies deposited in the ECAL (weight of 1.5) and in the HCAL (weight of 1.0). In the Level-3 isolation only charged-particle tracks near the vertex of the candidate muon are selected. This suppresses contributions from other p–p collisions thus making the Level-3 isolation requirement less dependent on instantaneous luminosity than the corresponding Level-2 isolation.

In both cases (Level-2 and Level-3 isolation) deposits associated with the candidate muon as well as from other muons in the event are excluded from the sum. The thresholds and cone sizes are adjusted in different pseudorapidity ranges in order to provide an optimal signal selection and background rejection: the usual cone size is $\Delta R = 0.24$ and the corresponding thresholds are defined as those that provide a uniform $\sim 90\%$ efficiency on the $W \to \mu \nu$ reference process.

A key point of a good trigger system is the flexibility. This is crucial not only to adapt the trigger to different luminosity conditions (which can be various, especially at the LHC start-up) and to unexpected physics scenarios but also to ensure a precise and unbiased measurement from the data of the HLT efficiencies. In Table 2.2 the main muon paths defined for the $10^{32}$ cm$^{-2}$ s$^{-1}$ conditions are listed but many other muon paths are under study, like prescaled paths with lower thresholds or calibration paths focused on the $Z$, $J/\psi$ and $Y$ di-muon mass peaks. The efficiency of the main muon trigger paths on the $W \to \mu \nu$ and $Z \to \mu \mu$ benchmark processes is shown in Table 2.3. The composition of the HLT muon rate is presented in Fig. 2.13, for the single-muon and double-muon paths. The decays from bottom and charm quarks dominate the rate at any $p_T$ threshold, while the contribution from pion and kaon decays at the chosen thresholds (16 GeV for single-muon and 3 GeV for double-muon) is almost negligible.

2.3 Muon Reconstruction

Muon reconstruction is performed in three stages:

- local reconstruction:
  the local pattern recognition starts from single hits to builds track stubs (called segments) separately in each subdetector (CSC and DT);
2.3 Muon Reconstruction

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Isolated µ</td>
<td>7</td>
<td>11</td>
<td>18.3 ± 2.2</td>
<td>18.3</td>
</tr>
<tr>
<td>Single µ</td>
<td>7</td>
<td>16</td>
<td>22.7 ± 1.5</td>
<td>37.7</td>
</tr>
<tr>
<td>Double µ</td>
<td>3.3</td>
<td>3.3</td>
<td>12.3 ± 1.6</td>
<td>48.5</td>
</tr>
</tbody>
</table>

Table 2.2: The main muon trigger paths at $10^{32} \text{cm}^{-2}\text{s}^{-1}$, for a total HLT rate of approximately 150 Hz. No prescale are foreseen on these paths.

<table>
<thead>
<tr>
<th>Signal</th>
<th>HLT Single µ eff.</th>
<th>HLT Single Isolated µ eff.</th>
<th>HLT Double µ eff.</th>
<th>L1×HLT acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \rightarrow µν$</td>
<td>86.9%</td>
<td>81.4%</td>
<td>-</td>
<td>76.7%</td>
</tr>
<tr>
<td>$Z \rightarrow µµ$</td>
<td>98.6%</td>
<td>95.8%</td>
<td>91.2%</td>
<td>98.1%</td>
</tr>
</tbody>
</table>

Table 2.3: HLT efficiencies and overall acceptance of muon trigger paths on $W \rightarrow µν$ and $Z \rightarrow µµ$ events. HLT efficiencies are determined on the total number of events passing the corresponding Level-1 criteria (single or di-muon Level-1 triggers, depending on the case). The overall (Level-1)×HLT acceptance is calculated on the total number of generated events. Both samples have been generated with the following cuts for the muons in the final state: $|\eta| < 2.4$ and $p_T > 10$ GeV.

- stand-alone reconstruction:
  the information of the whole muon system are merged (CSC, DT and RPC);

- global reconstruction:
  a global fit is performed using also the silicon tracker hits together with the hits in the muon system.

The reconstruction of the muons is completed by matching the muon track with the energy deposits in the calorimeters.

In Chapter 3 the DT local reconstruction and its performances are described in full details. Here a short overview of the stand-alone and global reconstruction and of the matching of the muon track with the calorimetric deposits is given (see [48] for a complete description). Also a brief description of the muon reconstruction performances is reported.
Muon Detection in the CMS Detector

Figure 2.13: HLT relaxed single-muon rate (left) as a function of the $p_T$ threshold for the reference Level-1 threshold of 7 GeV. HLT double-muon rate (right) as a function of the $p_T$ threshold for the reference Level-1 threshold of 3 GeV. The main components contributing to the rate are shown.

2.3.1 Stand-alone Muon Reconstruction

Track reconstruction within the muon system is based on Kalman filtering techniques. The starting point is the construction of a seed state from a combination of track segments and an initial estimate of the transverse momentum based on ad-hoc parameterizations. The track parameters are then propagated from one to the next layer of muon detectors taking into account material effects due to ionization and bremsstrahlung.

At each step the track parameters are used to identify the detector that most probably contains the next hit to be included in the trajectory. The best measurement is searched for on a $\chi^2$ basis. In case no matching hits (or segments) are found, the search continues in the next station.

In order to accept a muon track, at least two measurements, one of which must be of the DT or CSC type, must be present in the fit. This allows rejection of fake DT/CSC segments due to combinatorics. Moreover the inclusion of the RPC measurements helps in the reconstruction of low momentum muons and of those which escaped through the inter-space between the wheels (and the DT sectors), leaving only one DT fired station.

Once the hits are fitted and the fake trajectories are suppressed, the remaining tracks are extrapolated to the point of closest approach to the beam line. In order to improve the $p_T$ resolution a loose beam-spot constraint is applied.

2.3.2 Global Muon Reconstruction

Global muon reconstruction consists in extending the muon trajectories including hits in the silicon tracker system (silicon strip and silicon pixel detectors).
Starting from a stand-alone reconstructed muon, the muon trajectory is extrapolated from the innermost muon station to the outer tracker surface, taking into account the muon energy loss and the multiple scattering. An $\eta - \phi$ ROI is defined in the tracker. The track parameters of all the reconstructed silicon trajectories in this region are checked for compatibility, on a $\chi^2$ basis, with the initial muon track. In the case of very poor $\chi^2$ comparison which results in no matches, the matching is subsequently attempted by comparing the track separation in $\eta - \phi$ space and then Cartesian space.

For all matching pairs a track refit is performed using all the hits in the muon chambers and in the silicon tracker, finally fake tracks are suppressed.

### 2.3.3 Matching with Calorimetric Deposits

A large fraction of muons with transverse momentum below 6-7 GeV does not leave enough hits in the muon spectrometer to be reconstructed as stand-alone muons. Moreover, some muons can escape in the gap between the wheels. A complementary approach, which starts from the tracker tracks, has therefore been designed to identify off-line these muons and hence improve the muon reconstruction efficiency.

This alternative algorithm extrapolates the reconstructed silicon track to the calorimeter detectors (ECAL, HCAL, HO). The associated deposits are collected and they are used to compute compatibility variables which describe how well the observed signals fit with the muon hypothesis. The cuts on these variables must be carefully tuned in each physics analysis in order to balance the muon identification purity and efficiency in the most appropriate way for each physics case.

### 2.3.4 Reconstruction Performances

The muon reconstruction performances have been deeply tested in [49], the most important results will be reported here. The study has been performed using samples of single muons generated with different values of $p_T$ (from 1 GeV to 5 TeV) and flat distributions in $\eta$ and $\phi$. The muon reconstruction efficiency and resolution have been computed relying on a $\Delta R$ matching between the reconstructed and the simulated muon.

In Chapter 4 strategies to measure the muon reconstruction performances directly from data, exploiting the reference processes $Z \rightarrow \mu \mu$, $\Upsilon \rightarrow \mu \mu$ and $J/\psi \rightarrow \mu \mu$, are shown.
2.3.4.1 Reconstruction Efficiencies

Global, stand-alone and tracker reconstruction efficiencies are shown in Fig. 2.14 as a function of $\eta$, $\phi$ and $p_T$. These plots include the algorithmic efficiency as well as the geometric acceptance.

The efficiency of the matching of the stand-alone tracks with the inner tracker tracks, needed to define global muons, is not reported in the plots: it is of the order of 99.5% and, at the first order, it does not depend on the muon kinematic. The lost in matching efficiency is mainly due to the resolution of the stand-alone track parameters evaluated at the tracker surface.

![Efficiency plots](image)

**Figure 2.14:** Efficiencies of the different muon reconstruction steps as a function of $\eta$, $\phi$ and $p_T$.

The stand-alone reconstruction efficiency has a dip at $|\eta| \sim 0.3$ which is due to a discontinuity between the central wheel and the contiguous ones. The $0.8 < |\eta| < 1.2$ region is problematic for the seed-finding algorithm because the DT and CSC segments are used together to estimate the seed state. Moreover the stand-alone reconstruction efficiency has a periodic structure in the azimuthal angle due to the DT system segmentation in sectors. There is also a barrel inactive region at $\phi \simeq 1.2$ because of the presence of instrumentation services (chimneys) in two wheels. The overall integrated efficiency, for
momenta above 10 GeV, is more than 99%. For low momenta the efficiency decreases because a significant fraction of muons looses energy in the material before the muon stations or because of the bending in the magnetic field. At TeV momenta the muon reconstruction efficiency also decreases, even if very slowly, due to the increased bremsstrahlung probability.

The inner tracker is less affected by multiple scattering and energy loss than the muon system. Moreover the magnetic field in the tracker volume is homogeneous and almost constant. The integrated efficiency is almost constant for all $p_T$ values and its value is above 99.5%. The efficiency loss at $|\eta| \sim 0$ is due to the tracker geometry: the tracker is made of two half-barrels joined together, and the junction surface is at $\eta = 0$. Also $|\eta| \sim 1.8$ is a problematic region for tracker track reconstruction because of the transition from TID to TOB/TEC subsystems.

The global reconstruction efficiency is the product of the tracker, stand-alone and matching efficiency and for $p_T$ between 10 GeV and 1 TeV it is larger than 98%.

### 2.3.4.2 Reconstruction Resolution

In Fig. 2.15 the $q/p_T$ resolution (where $q$ is the muon charge):

$$
\frac{\delta(q/p_T)}{q/p_T} = \frac{q_{\text{rec}}/p_T^{\text{rec}} - q_{\text{sim}}/p_T^{\text{sim}}}{q_{\text{sim}}/p_T^{\text{sim}}},
$$

for the stand-alone, tracker and global reconstruction is shown as a function of $\eta$ and $p_T$ in the barrel region.

The peaks in $|\eta|$ correspond to the problematic regions already discussed in the analysis of the efficiencies. The resolution degrades as the pseudorapidity increases because of the more complex environment in which the endcaps are embedded: the integral of the magnetic field decreases, the magnetic field presents large inhomogeneities and it is no longer solenoidal.

The dependence of the $p_T$ resolution on the $p_T$ itself is described by the following formula

$$
\frac{\delta p_T}{p_T} = \frac{0.0136}{\beta B L} \sqrt{\frac{x}{X_0}} \sqrt{\frac{4A_N}{N}} \left( \frac{\sigma \cdot p_T}{0.3BL^2} \right) \sqrt{4A_N},
$$

where $\beta = v/c$, $x/X_0$ is the thickness of the scattering medium in radiation lengths, $B$ is the magnetic field value, $L$ the length of the tracking system, $N$ the number of measurements, $\sigma$ their individual errors and

$$A_N = \frac{180N^3}{(N-1)(N+1)(N+2)(N+3)}.$$
Figure 2.15: $q/p_T$ resolution for the stand-alone (above, left), tracker (above, right) and global (below, left) reconstruction as a function of $\eta$. $q/p_T$ resolution for the global reconstruction as a function of $p_T$ (below, right).
The first term of eq. 2.2 represents the contribute of multiple scattering and it is constant with $p_T$, while the second term is directly related to the precision of the hit measurements and it increases linearly with $p_T$. At low $p_T$ (smaller than 100 GeV) the first term dominates in the stand-alone reconstruction, therefore the tracker resolution is sensibly better than the stand-alone one. At higher $p_T$ the second term becomes dominant and the resolution increases with $p_T$. In this high $p_T$ region, the worsening of the stand-alone reconstruction resolution is limited by the big lever arm.

2.4 Muon Isolation

The isolation requirement from hadronic activities strongly reduce the QCD background. The role of isolation in the muon trigger selection has been already discussed in Sec. 2.2, here the offline muon isolation features are discussed.

The standard cone size around the muon is $\Delta R = 0.3$ and the most used variables are the $p_T$ sum of the tracks, the weighted $E_T$ sum of the ECAL and HCAL towers or some combinations of these two variables.

In Fig. 2.16 the tracker isolation efficiencies on $Z \rightarrow \mu\mu$ and on a QCD muon sample are compared. In Fig. 2.17 the same efficiency on the $Z \rightarrow \mu\mu$ sample as a function of muon $\eta$ and $p_T$ is shown. Any sizable dependence can induce a bias in the offline analysis. The efficiency is relatively independent on the muon $p_T$, with a slightly lower value at low $p_T$ due to an increased fraction of muons correlated in direction with the hadronic recoil activity in the event. No substantial dependence on $\eta$ is observed.
Figure 2.16: Isolation efficiency on $Z \rightarrow \mu\mu$ and a generic QCD sample for several cut values ($p_T$ sum of the tracks inside the $\Delta R = 0.3$ cone around the muon must be smaller than 2-6 GeV).

Figure 2.17: Isolation efficiency on $Z \rightarrow \mu\mu$ as a function of $p_T$ (left) and $\eta$ (right) for $p_T$ sum of the tracks < 3 GeV (blue). The average efficiency of this cut is denoted with the horizontal green line. Also the isolation efficiency for a similar cut on the ratio of the track $p_T$ sum over the muon $p_T$ (< 0.0925) is shown (red).
Chapter 3

The Drift Tube Detector: Calibration and Local Reconstruction

The barrel region ($|\eta| < 1.2$) of the CMS return yoke is instrumented with DT chambers. A general description of the chamber design and of the read-out and trigger electronics is reported in previous chapter (Sec. 2.1.2.1). Here, after a brief introduction on the DT working principles (Sec. 3.1.1), the DT calibration and local reconstruction algorithms are presented and their performances are studied using samples of simulated muons (Sections 3.1.2 and 3.1.3).

Some calibration issues can not be tested on simulated data, like the inter-channel synchronization inside each chamber (due to different cable lengths), noise and dead channels. These effects are not simulated but they were extensively studied during the commissioning with cosmic data. In Sec. 3.3 the experience with the DT calibration and local reconstruction algorithms during the detector commissioning is presented, with particular emphasis on the Magnet Test and Cosmic Challenge (MTCC) performed in summer 2006.

3.1 Algorithms Description and Results on Simulated Data

The sub-detector calibration and the sub-detector level reconstruction (also called “local” reconstruction) are the groundwork for an efficient and precise detection of the so called “physics objects” (muon, electron, photon, jet and so on). Dedicated algorithms were developed and tested since many years exploiting detailed simulations of the detectors in realistic operating conditions. A full description of the DT simulation in the CMS software, on which the results here presented are based, can be found in [50].
3.1.1 Introduction

3.1.1.1 DT Working Principles

The CMS drift chambers [38, 40] rely on the detection of the ionization electrons produced in an Ar/CO$_2$ gas mixture by incoming particles. The drift time of such electrons in a properly shaped electrostatic field is measured to get the information about the spatial coordinates of the ionizing event.

A minimum ionizing particle will produce, on average, about 100 ionization electrons in the cell volume. Once they are produced along the trajectory of the particle, they drift in the electrostatic field generated by the central anode wire, maintained at a positive potential, and the cathode strips, glued on the I-beam profile, which have negative potential. The drift field is shaped in order to have a linear space-time relationship over the entire volume; this is achieved with the positively-biased strips glued at the center of the aluminium planes delimiting the cell volume.

The ionization electrons are eventually collected by the anode wire where a strong electric field, increasing as $1/r$, accelerates them enough to produce secondary ionization and hence an avalanche. A gain of about $10^5$ is achieved. The CO$_2$ present in the gas admixture acts as quencher. Thanks to its large photo-absorption cross section, it absorbs photons produced during the avalanche development, keeping the avalanche region limited.

The electrons produced in the avalanche are collected by the wire while the positive ions move toward the cathode. The induced signal is amplified and discriminated against a configurable threshold by the front-end electronics and it is then sent to the read-out electronics performing the TDC measurement. The final measured time delivered by the DAQ is called “digi” in the CMS jargon.

Electrons produced at a time $t_{\text{ped}}$ by the incoming particle migrate toward the anode with a velocity $v_{\text{drift}}$ and reach the anode at a time $t_{\text{TDC}}$, which is the time measured by the TDC. The distance of the track from the anode wire is therefore given by

$$x = \int_{t_{\text{ped}}}^{t_{\text{TDC}}} v_{\text{drift}} \cdot dt. \quad (3.1)$$

The CMS DT’s do not need any external device to determine the time $t_{\text{ped}}$. The on-chamber trigger electronics exploits the redundancy of measurements in three consecutive staggered layers with an extension of the meantimer technique [44] to recognize aligned hits and to determine the bunch crossing when the muon has been produced.

In the reconstruction of track hits, the time pedestal is extracted directly by the measurement distribution with the calibration procedure described in Sec. 3.1.2.
The measurement of the track distance from the wire \( (x) \) requires understanding of the time-space relationship of eq. 3.1.

The major factors which can influence the drift velocity are:

- electric field strength and direction and gas pressure. To limit the dependence from these two factors, the working point is chosen to have a value of \( E/p \) corresponding to a saturated drift velocity: in the gas mixture used for the CMS DT’s the drift velocity saturates for fields of about 1.9 kV/cm. The cell is therefore designed in such a way to avoid regions of field lower than this value, reducing the sensitivity to local field variations;

- gas composition and temperature. The pressure, temperature and purity of the mixture are continuously monitored. In particular the oxygen concentration is always kept below 500 ppm;

- presence of external factors such magnetic stray fields. The presence of a magnetic field modifies the drift properties of an electron swarm. The Lorentz force applied to each of the moving charges bends its trajectory. In case of a homogeneous magnetic field along the wire, the main consequence would be an effective lower drift velocity. The field lines are distorted by the presence of the magnetic field, as shown in Fig. 3.1 for a simulation of the cell. In CMS the situation is complicated by the fact that the residual magnetic field in the cell volume will not be homogeneous, as shown in Fig. 2.11.

For tracks inclined with respect to the normal to the layer in the measurement plane the time-distance relation is modified by the fact that the electrons having the shortest drift time are not those produced in the mid plane of the drift cell. The effective drift-velocity is therefore higher. No deviation from linearity is observed for tracks inclined in a plane parallel to the wire.
Two algorithms are available in the CMS reconstruction code. The first reconstruction algorithm is based on the assumption of a constant drift velocity within the entire cell. In this case, eq. 3.1 becomes

\[ x = (t_{TDC} - t_{\text{ped}}) \cdot v_{\text{drift}}^{\text{EFF}} = t_{\text{drift}} \cdot v_{\text{drift}}^{\text{EFF}} \]  

(3.2)

where \( v_{\text{drift}}^{\text{EFF}} \) is the effective average drift velocity.

The goal of the calibration procedure is in this case to determine the time pedestal \( (t_{\text{ped}}) \), which is needed to extract the drift time \( (t_{\text{drift}}) \) from the TDC measurement \( (t_{TDC}) \), and the average drift velocity \( v_{\text{drift}}^{\text{EFF}} \).

The value of \( v_{\text{drift}}^{\text{EFF}} \) depends on many parameters, as we have seen. However, the detector can be subdivided in properly limited spatial regions where these parameters can be assumed approximately constant. The calibration procedure is performed with the correspondent granularity, therefore the computed drift velocity is averaged under local variations of such parameters in each region.

The second reconstruction algorithm is based on a parameterization of the cell response [51] obtained with GARFIELD [52]. This parameterization includes the dependence on the track impact angle, \( \alpha \), and on the stray magnetic field \( B \):

\[ x = f((t_{TDC} - t_{\text{ped}}), \alpha, B) \]  

(3.3)

In this case the only quantity to be calibrated is \( t_{\text{ped}} \), as the dependency on the relevant parameters is already accounted for by the parameterization.

The procedure to determine the time pedestals is described in Sec. 3.1.2.1. Sec. 3.1.2.2 introduces the calibration of the drift velocity and the assignment of the uncertainty on the hit position. Finally, Sec. 3.1.2.3 outlines the reciprocal dependence between the time pedestal and the drift velocity.

It should be noted that the residual magnetic field and the track angle also influence the intrinsic cell resolution due to their effect on the cell non-linearities. Correct estimation of the hit uncertainty is important for the track fit; for this reason, the calibration algorithm must also be able to assign correct uncertainty to the reconstructed hits.

Moreover the spatial resolution of a drift chamber is limited by the diffusion of the ionization electrons during the drift, the fluctuations of the primary ionization processes and, finally, by the knowledge of the space-time relationship; the cell resolution of the CMS DT chambers is about 180 – 200 \( \mu \)m.

### 3.1.1.2 Labeling and Reference Frames

The chamber segmentation follows that of the iron yoke, consisting of five wheels along the \( z \) axis, each divided into 12 azimuthal sectors. The wheels are numbered from -2 to +2, sorted according to global CMS \( z \) axis, with wheel 0 situated in the central region around \( \eta = 0 \).
Within each wheel, chambers are arranged in four stations at different radii and are named MB1, MB2, MB3 and MB4 as shown in Fig. 3.2. The first and the fourth station are mounted on the inner and outer face of the yoke, respectively; the remaining two are installed in slots within the iron plates.

In each wheel, a station consists of 12 chambers, one per sector, except for MB4 where 14 chambers are present. Sector numbering increases counterclockwise when looking at the detector from the positive \( z \) axis, starting from sector number 1 which contains the vertical chambers matching the positive \( x \) axis in the CMS global reference frame. The additional two chambers in MB4 are numbered 13 and 14 according to the scheme shown in Fig. 3.2.

![Figure 3.2: Numbering of muon barrel stations and sectors.](image)

The convention on chamber local reference frames used in the CMS simulation and reconstruction software is shown in Fig. 3.3.

Superlayers are numbered from 1 (innermost \( r-\phi \)) to 3 (outermost \( r-\phi \)). Number 2 is thus always the \( r-z \) superlayer, when present.

Layers are numbered from 1 (innermost) to 4 (outermost). A local reference frame is associated to each layer; the origin is placed at the centre of the layer, the \( x \) axis along the measured coordinate and the \( y \) axis along the wires, pointing towards the superlayer’s front-end side. Cell number increases with \( x \) increasing.

Superlayers have a local reference frame oriented in the same way as the layers, but with the origin at the superlayer centre.

The chamber reference frame has the origin in the chamber centre and is oriented as the \( r-\phi \) superlayer reference frames, i.e. with the \( x \) axis along the
coordinate measured by the $r$-$\phi$ superlayers and the $y$ axis along the coordinate measured by the $r$-$z$ superlayer, pointing towards the $r$-$\phi$ front-end side.

With this choice of reference frames, the $z$ axis of all local reference frames points toward the interaction region.

Chambers are installed in CMS with the front-end of $r$-$\phi$ superlayers in the side farther from the interaction point (i.e. with the chamber $y$ axis pointing outwards). This allows a rough compensation, in $r$-$\phi$ superlayers, of the different time-of-flight of particles at different $\eta$ with the propagation time along the wires. The chamber local reference frames are oriented accordingly: in positive wheels (+1, +2) the chamber $y$ axes are oriented along the global CMS $z$ axis, while in negative wheels the $x$ axis points towards the opposite direction. In wheel 0, chambers are oriented alternately in the two ways in the different sectors.

3.1.2 Calibration

3.1.2.1 Calibration of the Time Pedestals

A DT measurement consists in a TDC time which contains the drift time of the ionization electrons in the cell plus contributions from

- the time-of-flight (TOF) of the muon from the interaction point to the cell;
- the propagation time of the signal along the anode wire;

Figure 3.3: Schematic view of a DT chamber, showing the conventions on superlayer, layer and wire numbering and the orientation of reference frames.
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- delays due to the cable length and read-out electronics;
- the time latency due to the Level-1 trigger.

These offsets must be estimated and subtracted from the TDC time during reconstruction. The jitter in the drift time deriving from the uncertainties of this procedure directly contributes to the DT resolution.

The extraction of the drift time from the TDC measurement is performed in several consecutive steps.

- **Inter-channel synchronization.**
  First, it is necessary to correct the measured TDC times for the relative difference in the signal path length to the readout electronics of each wire. This relative difference is measured for each wire by sending simultaneous (with an error smaller than 150 ps) “test-pulses” to the front-ends and computing the difference between the measured times, called $t_0$. This relative correction is usually between 1 and 8 ns. Once the $t_0$ is subtracted, the resulting TDC times for the different channels within the chamber are synchronized among them.

- **Absolute offset determination.**
  Once the channels are synchronized, it is possible to compute the absolute offset of the drift time distribution. This offset, called $t_{\text{trig}}$ because of its dependence on the trigger latency, allows the extraction of the drift time from the TDC measurement. The $t_{\text{trig}}$ is directly estimated from the distribution of the digi times. Its value depends on the specific DAQ setup and is usually of the order of a few $\mu$s.

Note that the determination of these two delays does not completely solve the problem of synchronization of the digi times, as normally, due to the limited available data, the $t_{\text{trig}}$ is computed for a group of cells together, e.g., all cells in a superlayer. In this case, the measured $t_{\text{trig}}$ includes the average TOF and the average signal propagation time of the muons that crossed the superlayer. If the chamber is uniformly illuminated, which is the case for $p-p$ collisions, this average TOF is approximately equivalent to that of a muon crossing the superlayer center, while the average signal propagation time is equivalent to the propagation time for a signal produced in the middle of the wire.

Therefore, further corrections for these two effects can be computed as soon as the three-dimensional hit position within the chamber is known, after the hits are associated into 3D track segments. Specifically, if the $t_{\text{trig}}$ is computed for a full superlayer uniformly illuminated:

- the 3D position obtained from the segment extrapolation to the hit plane, if available, is used to correct the TOF with respect to the superlayer center;
• the hit coordinate along the wire is used to correct the propagation time with respect to the middle of the wire, assuming a propagation velocity of 0.244 m/ns, as directly measured on test beam data [53].

These corrections can be as high as \( \sim 2 \) ns for the TOF and \( \sim 6 \) ns for the signal propagation delay and they can be adapted or switched off in case of different running conditions. This is the case, for example, of cosmic data, where the previous definition of the TOF can not be applied, or test beam data, where the chamber is usually illuminated in a relatively small region. Particular care has been taken to provide enough flexibility for such cases.

**Inter-channel synchronization** The analysis of test-pulse data is not only useful for the inter-channel synchronization, as already stated, but also because the spread in the measured test-pulse times (\( \sigma \) of the test-pulse peak) in each channel is an interesting quantity to monitor the status of the read-out on-chamber electronics. Therefore the aim of the \( t_0 \) calibration consists in the computation of the mean and the \( \sigma \) of the test-pulse peak in each channel. This procedure is complicated by the presence of noise, with uniform time distribution, and of additional peaks in the TDC time window due to various service signals (e.g., the signal for channel masking). Particular care is taken in the calibration procedure to exclude the noise from the mean and \( \sigma \) computation and in order to be sure to consider the right peak in the time window.

Because of the big number of channels (\( \sim 172000 \)), the storing of the measured times in each channel (e.g., in the form of histograms) would require too much CPU memory, hence an exact computation of the \( \sigma \) of the peak in each channel would require to run twice on the data. To save CPU time and memory an approximate formula has been used to compute the \( \sigma \) “on-fly” [54].

The mean value of the peak in each channel corresponds to the entire time of signal propagation from the pulse injector to the read-out electronics, while for the inter-channel synchronization the relative difference of this propagation time in each channel is needed. Hence a reference time must be chosen: the reference offset is somehow arbitrary for the \( t_0 \) calibration by itself, but it has an impact on the subsequent calibration of the absolute \( t_{\text{trig}} \) offset. A meaningful choice is taking as reference the average of test-pulse times measured in all the channels of each chamber. In this way all the relative delays due to the on-chamber electronics are stored in the \( t_0 \) values, while the electronic delays external to chamber are stored in the \( t_{\text{trig}} \) values.

A final additional correction must be considered in the \( t_0 \) calibration. In each superlayer the pulse injection lines of odd and even layers are different. Therefore the two kinds of layers must be synchronized, on average, among them before computing the relative \( t_0 \) in each channel.
Determination of the $t_{\text{trig}}$ Offset  Since the digi times of the different channels in a chamber have already been synchronized by subtracting the $t_0$ offset, the $t_{\text{trig}}$ can be computed with every possible granularity within the chamber. The usual choice is to compute it superlayer by superlayer, as a compromise between accuracy in accounting for the average TOF and the quantity of available data.

Due to its dependency on the trigger latency, the $t_{\text{trig}}$ pedestal must be calibrated each time the trigger configuration and synchronization change. Moreover, as it accounts for the average contribution of the TOF and the signal propagation along the anode wire, the $t_{\text{trig}}$ also depends on the running conditions: these contributions are different if the superlayer is not uniformly illuminated, as, for example, in test beam data taking. This has to be taken into account when using pedestals in the reconstruction.

The pedestal can be estimated directly from the distribution of the digi times, which is usually referred as the *time box*. Some examples of such distribution are shown in Fig. 3.4 for $r$-$\phi$ and $r$-$z$ superlayers in different wheels. The drift times varies between 0, for muons passing close to the anode wire, to about 380 ns, for muons passing close to the cathode, but the full drift time distribution is shifted of a fixed value which is the $t_{\text{trig}}$ pedestal. In case of a perfect linear cell behavior the distribution would have a regular box shape. The peak at low time values is due to the non-linearity close to the anode wire, the rest of the cell shows a good linearity in $r$-$\phi$ superlayers of all the wheels and in $r$-$z$ superlayers of wheel 0. The non-linearities in $r$-$z$ superlayers of the external wheels are due to the big track angles and the residual magnetic field (as shown in Fig. 2.11).

In order to compute the pedestal it is necessary to find a feature of this distribution which can be identified in an unambiguous and automatic way. Earlier studies have shown that a suitable feature is the inflexion point of the rising edge, which can be obtained from a Gaussian fit of the derivative of the time box distribution [55, 56]. This method, however, is sensitive to noise and spikes due to the read-out electronics. To implement an automatic procedure to fit the drift time box in unattended mode for all the superlayers of the 250 DT chambers, we developed a different, more robust method, based on a fit of the rising edge of the drift time distribution with the integral of the Gaussian function (the so-called *error function*):

$$f(t) = \frac{1}{2} I \left[ 1 + \text{erf} \left( \frac{t - \langle t \rangle}{\sigma \sqrt{2}} \right) \right],$$  \hspace{1cm} (3.4)$$

where the normalization $I$, the standard deviation $\sigma$ and the mean $\langle t \rangle$ are free parameters of the fit. In Fig. 3.4 on the right an example of this fit is shown for a time box of a $r$-$z$ superlayer illuminated during a muon test beam.
Figure 3.4: Distribution of the digi times in r-φ and r-z superlayers in different wheels, all the time boxes have the same arbitrary normalization (left). Fit to the time box rising edge for a given superlayer (right).

In Figures 3.5 and 3.6 the distribution of the positions of the inflexion points (⟨t⟩) for all the superlayers is shown. A sample of 1.2 M Z/γ → μμ simulated events has been used. It should be noted that the jittering of the electronic delays and of the trigger time latency are not simulated: during the digitization a fixed offset of 500 ns is added to the simulated drift time. Moreover the TOF from the interaction point to the center of each superlayer is already subtracted at the digitization level for practical reasons (the trigger emulator need already synchronized digis as input). Therefore the only remaining contribution to the t_{trig} is the time of propagation of the signal along the wire.

The wire length is the same in all the r-φ superlayers except for the ones in sector 2 of wheel -1 and in sector 4 of wheel 1. In these detector regions two “chimneys” are installed in order to accommodate all the services (cooling, power supply, etc.). The corresponding chambers have smaller size in the view and therefore they have shorter wires in r-φ superlayers. The difference with respect to the standard wire size is about 40 cm which corresponds to a difference in the signal propagation time of about 1.5 ns (the propagation velocity has been taken from [53]). This effect is clearly visible in Fig. 3.5. All the other r-φ superlayers have the same inflexion point with fluctuations comparable to the TDC measurement precision (the finite TDC step size is 0.78 ns).

The wire length in the r-z superlayers increases of about 45 cm from MB1 to MB2 and it increases further of about 50 cm from MB2 to MB3. Each increase corresponds to about 2 ns in the signal propagation time. This effect is clearly visible in Fig. 3.6.

The inflexion point of the rising edge of the time box does not directly represent the time pedestal of the distribution, but can be related to it by defining

\[ t_{trig} = ⟨t⟩ - k \cdot σ, \]  

(3.5)
Figure 3.5: Positions of the inflexion points (i) for r-superlayers computed with 1.2 M \( N/Z \) simulated events.
Figure 3.6: Positions of the inflection points (h) for \( r-z \) superlayers computed with 1.2 M \( \sim \) simulated events.
where $\sigma$ is the standard deviation of the Gaussian function used to fit the time box rising edge and $k$ is a factor that is tuned by requiring the minimization of the residuals on the reconstructed hit position, superlayer by superlayer. A typical value of the $k$ factor is 1.3.

The $\sigma$ parameter is an estimation of the rising edge slope and typical values are between 3.5 ns and 5.5 ns, depending on the superlayer kind and position. The major contribution are due to the intrinsic jittering in the electron drift time (about 2-3 ns), the spread of the propagation time of the signal along the wire (about 3 ns) and the spread of the TOF (less than 1 ns).

In order to obtain meaningful residual distributions it is necessary to have a preliminary estimation of the $t_{\text{trig}}$ at least correct to 10 ns, therefore the fit of the time box rising edge has to be performed before the $k$ factor optimization can be done.

It should be noted that the optimal value of $t_{\text{trig}}$ depends on the algorithm used in the reconstruction. In particular, the cell parameterization has a small, arbitrary, intrinsic offset deriving from the way the signal arrival time is computed in the GARFIELD simulation. For this reason a fine tuning of the $t_{\text{trig}}$ has to be done differently for the two reconstruction algorithms.

In addition, the effect of a mis-calibration of the time pedestal is different for the two reconstruction algorithms.

If the reconstruction is performed using a constant drift velocity over the entire cell, a $t_{\text{trig}}$ not perfectly calibrated results in an error on the estimated drift time and therefore in a constant offset for all the reconstructed distances from the wire. This is illustrated for Monte Carlo simulated $p$-$p$ collisions in Fig. 3.7 which shows the residuals on the distance from the wire ($|x_{\text{reco}}| - |x_{\text{sim}}|$) for two particular choices of the time pedestal: the “optimal” value and a $t_{\text{trig}}$ mis-calibrated of $\Delta t = 6$ ns $^1$. The error on the pedestal affects the mean value of the distribution of a quantity given by $-\Delta t \cdot v_{\text{drift}}$, while the standard deviation of the Gaussian fit is essentially unaffected, being dominated by the non-linearities responsible for the modulation shown in the scatter plots of Fig. 3.7. This independence of $\sigma$ on the actual value of $t_{\text{trig}}$ allows $t_{\text{trig}}$ to be optimized superlayer by superlayer by tuning the $k$ factor of eq. 3.5 to minimize the mean of the residual distribution.

Note that Fig. 3.7 shows the distributions obtained for all the muon tracks originating in $p$-$p$ collisions recorded in the $r$-$z$ superlayers of wheels $\pm 2$, i.e., the superlayers in which the effects of non-linearity are expected to be larger, because of the bigger average values of the track incident angles with respect to the direction normal to the chambers and the larger values of the residual magnetic field in the chamber volume.

$^1$This value of the pedestal corresponds to an extreme case of mis-calibration, chosen for illustration purposes. The $t_{\text{trig}}$ can be usually calibrated with much higher accuracy.
The Drift Tube Detector: Calibration and Local Reconstruction

Figure 3.7: Residuals between the reconstructed and the simulated hit distances from the wire ($d = |x|$) for $r$-$z$ superlayers in wheels ±2. The plots on the right show the residuals as a function of the distance from the wire. The plots have been obtained using a constant drift velocity (a) with the optimal value of the $t_{\text{trig}}$ and (b) with a $t_{\text{trig}}$ 6 ns greater than the optimal one. No further corrections for the TOF or the time of signal propagation along the wire have been applied.

The effect of a mis-calibration of the $t_{\text{trig}}$ pedestal is more complex when the reconstruction is performed using the GARFIELD parameterization. As this parameterization accounts for the cell non-linearity as a function of the drift time, an offset in the input time does not simply produce an offset in the mean value of the residuals, but also implies that the non-linearities are accounted for incorrectly, resulting in a wider residual distribution. This is illustrated...
in Fig. 3.8, which again shows the residuals of the reconstructed hit distances from the wire in the $r$-$z$ superlayers of wheels $\pm 2$ for the two extreme choices of the $t_{trig}$ pedestal considered above. It can be observed that, since the parameterization corrects for the non-linearities, the presence of an offset in the $t_{trig}$ introduces artificial deviations, leading to a broadening of the residual distribution in addition to a shift of the mean value. This effect can be used for the optimization of the $t_{trig}$ value, which can be simply performed by minimizing the width of residuals: the optimal $t_{trig}$ value is the value for which the parameterization of non-linearities best fits the input data.

It should be noted that in real data the residuals will be computed with respect to the reconstructed 3D segment and this will introduce systematic effects on the $k$ factor optimization to be studied.

### 3.1.2.2 Calibration of the Drift Velocity

The drift velocity depends on many parameters, including the gas purity and condition and the electrostatic configuration of the cell. Moreover, the presence of stray magnetic field and the angle of incidence of the track (indicated with $\alpha$ in Fig. 3.9) influence the effective drift velocity. In particular, the effect of the track angle is due to the fact that the electrons with smaller drift time are not the ones produced in the cell median plane. This effect has been measured and the results are reported in [40].

The working condition of the chambers will be monitored continuously and important variations are not expected among different regions of the spectrometer. The situation is different for the stray magnetic field and for the track impact angle: these parameters will vary substantially, on average, moving from chamber to chamber and also from superlayer to superlayer due to the different positions within the return yoke and to the different pseudorapidities of the impact angles in the $r$-$z$ cells. For this reason, the reconstruction algorithm based on a constant drift velocity requires a calibration procedure that allows the average velocity to be found separately for different groups of cells.

To fulfill these requirements, a calibration algorithm based on the so-called meantimer computation [44] has been developed and is described below. This technique estimates the maximum drift time and therefore the average drift velocity in the cell. Moreover, it also measures the cell resolution, which can be used as an estimate of the uncertainties associated to each measurement.

#### Meantimer Technique

The meantimer formulas are relations among the drift times produced by a track in consecutive layers of a superlayer ($t_i$) and the maximum drift time ($T_{max}$) in a semi-cell (i.e. half cell), under the assumption of a constant drift velocity. Even with small deviations from this assumption, as in the case of the DTs, the average of the meantimer distribution contains
Figure 3.8: Residuals between the reconstructed and the simulated hit distances from the wire ($d = |x|$) for $r$-$z$ superlayers in wheels $\pm 2$. The plots on the right show the residuals as a function of the distance from the wire. The plots have been obtained using the GARFIELD parameterization with the optimal value of the $t_{\text{trig}}$ (a) and with a $t_{\text{trig}}$ 6 ns bigger than the optimal one (b). No further corrections for the TOF or the time of signal propagation along the wire have been applied.

information about the average drift velocity in different regions of the cell, since it is computed using drift times produced by hits all over the gas volume. The mathematical expression of the meantimer relation depends on the track angle and on the pattern of cells hit by the track. In the easiest case the track crosses a semi-column of cells, i.e., the interested wires are at the same position for
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Figure 3.9: Schematic view of a superlayer showing the track segment angle convention and the pattern of semi-cells crossed by the track.

Each couple of staggered cells. In this simple case the correspondent meantimer relation is

\[ T_{\text{max}} = \frac{(t_1 + t_3)}{2} + t_2 \]  

(3.6)

The meantimer relations for different track angles and patterns of hit cells are listed in [1]. It should be noted that not all the track geometrical configurations can be used because in some cases the relation between drift times is independent of \( T_{\text{max}} \). The proper meantimer formula is chosen track by track, using the direction and position information provided by the three-dimensional segments in a superlayer. This implies an iterative calibration procedure, starting with values of the drift velocity and of \( t_{\text{trig}} \) that already result in efficient pattern recognition and segment reconstruction.

The meantimer is normally computed superlayer by superlayer, assuming the same effective drift velocity in all layers. It may be interesting, however, to calibrate the average drift velocity with finer granularity to take into account possible local variations within the layer quadruplet due to magnetic inhomogeneities.

The mechanical precision of the wire and layer positions inside the superlayers is of the order of 100 \( \mu \)m and it should be known to 10 \( \mu \)m after the first alignment procedure. This precision corresponds to a bias of 1.8 ns (0.18 ns) on the measured drift times and it causes a different uncertainty on the \( T_{\text{max}} \) depending on the formula, the consequent error on the drift velocity is of the order of 1% (0.1%) or less.

The calibration procedure of the drift velocity consists of the following steps:

- a Gaussian is fit to the meantimer distribution for each track pattern \( j \) to estimate the mean value \( T_{\text{max}}^j \), the standard deviation \( \sigma_T^j \), and the error on the mean \( \sigma_T^j / \sqrt{N_j} \) (where \( N_j \) is the number of entries in the distribution);
The weighted average of the values of $T_{\text{max}}^j$ is computed where the weights are taken as $N_j/(\sigma_T^j)^2$:

$$\langle T_{\text{max}} \rangle = \frac{\sum_j T_{\text{max}}^j N_j}{\sum_j N_j (\sigma_T^j)^2}.$$ \hspace{1cm} (3.7)

This accounts for the relative importance of the different cell patterns in the computation of the maximum drift time.

Once $\langle T_{\text{max}} \rangle$ is computed it is straightforward to find the average drift velocity through the relation:

$$v_{\text{drift}} = \frac{L/2}{\langle T_{\text{max}} \rangle};$$ \hspace{1cm} (3.8)

where $L$ is the width of the cell. The effective drift velocity computed for each superlayer is then stored in a database to be used by both the HLT and the off-line hit reconstruction.

In Fig. 3.10 the values of the drift velocity in each superlayer is shown. A sample of 1.2 M $Z/\gamma^* \rightarrow \mu\mu$ simulated events has been used.

The effects of the track angle and the residual magnetic field on the drift velocity has been studied with test beam data on chamber prototypes [40], the results are reported in Fig. 3.11. These old studies have been carried out on chambers with a cell design slightly different from the final one, however the overall behavior can be taken as reference.

The longitudinal angle, which is the azimuthal angle for $r-z$ superlayers and the polar angle for $r-\phi$ superlayers, slightly decreases the drift time, resulting in a little increase of the drift velocity. The transverse angle, which is the polar angle for $r-z$ superlayers and the azimuthal angle for $r-\phi$ superlayers, strongly decreases the drift time, resulting in a sizable increase of the drift velocity. The magnetic field perpendicular to the chamber plane, which is the radial component ($B_r$) shown in Fig. 2.11, increases the drift time, resulting in a decrease of the drift velocity. The magnetic field parallel to the drift direction have obviously no effect while the component parallel to the wires (which, for $r-\phi$ superlayers corresponds to the $B_z$ component in Fig. 2.11) would also decreases the drift velocity. However this component is always too small to produce any effect.

In Fig. 3.10 the regions with small track angle and negligible magnetic field (wheel 0, $r-\phi$ and $r-z$ superlayers) have a drift velocity of about 55.3 $\mu$m/ns. In the other $r-\phi$ superlayers there is a slightly bigger drift velocity because the longitudinal (polar) angle increases, with the exception of MB1 in wheel $+/1$ and MB1 and MB2 in wheel $+/2$ where the radial component of the magnetic field induces a strong reduction of the drift velocity. In the $r-z$ superlayers the
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![Drift velocity graph]

**Figure 3.10:** Drift velocity in each $r$-$\phi$ superlayer (above) and $r$-$z$ superlayer (below) computed with $1.2 M \ Z/\gamma^* \rightarrow \mu\mu$ simulated events.

Drift velocity increases in the external wheels because of the transverse (polar) angle, with the exception of MB1 in wheel +/-2 where the radial component of the magnetic field induces a strong reduction of the drift velocity.

**Estimate of the Cell Resolution** The meantimer technique allows the estimation of the cell resolution and hence the uncertainties on the reconstructed distance.

The standard deviation of the meantimer distribution ($\sigma^j_T$) is a measurement of the resolution of $T^j_{\max}$. It can be therefore used to estimate the uncertainty on the measurement of the drift times ($\sigma^j_t$) with a relation that depends on the particular formula used to compute the meantimer. In the case of tracks crossing
Figure 3.11: Effects of track angle and residual magnetic field on drift velocity or on maximum drift time (in inverse proportion to the drift velocity). These plots are taken from [40].

a semi-column of cells (123LRL or 123RLR in Fig. 3.9), given the meantimer relation listed in [1], the time resolution can be computed as

$$\sigma_t^j = \sqrt{\frac{2}{3}} \cdot \sigma_T^j,$$

which is valid under the assumption that the uncertainties are the same for all three layers used in the meantimer computation.

Since the cell resolution depends on the track angle, an average effective value is computed by averaging the different values obtained for the contributing cell patterns weighted on the number of entries in each meantimer histogram ($N_j$):

$$\langle \sigma_t \rangle = \frac{\sum_j \sigma_T^j \cdot N_j}{\sum_j N_j}.$$  

The resolution of the reconstructed distance is therefore given by:

$$\sigma_d = v_{\text{drift}} \cdot \langle \sigma_t \rangle.$$
This value is used during the reconstruction to assign the uncertainties to the one-dimensional RecHits in the gas volume. These uncertainties include the effect of the cell non-linearities (as those shown in Fig. 3.7) only on average, therefore their dependence on the distance from the wire cannot be taken into account with this method.

### 3.1.2.3 Interplay of Meantimer Computation and Time Pedestals Determination

Reconstruction using a constant drift velocity requires both the calibration of the time pedestals needed for synchronization and the calibration of the average drift velocity. These two tasks are not independent since on one hand the computation of the meantimer requires knowledge of the time pedestals and on the other hand fine tuning of $t_{\text{trig}}$ is based on analysis of the residuals, which are directly affected by a mis-calibration of the drift velocity.

If the determination of $t_{\text{trig}}$ is affected by a systematic shift $\Delta t$:

$$t_{\text{trig}}' = t_{\text{trig}} + \Delta t, \quad (3.12)$$

the meantimer will be consequently biased by a quantity that depends on the particular meantimer formula among those listed in [1]. In the case of tracks crossing a semi-column (123LRL or 123RLR in Fig. 3.9) we can evaluate the effect on $T_{\text{max}}$ as

$$T_{\text{max}}' = T_{\text{max}} - 2\Delta t. \quad (3.13)$$

In a simplified scenario where this particular pattern is the one determining the meantimer calculation ($T_{\text{max}} \approx T_{\text{max}}'$) the bias on $t_{\text{trig}}$ determination will result in a mis-calibration of the drift velocity $\Delta v_{\text{drift}}$, which can be estimated as

$$v_{\text{drift}} + \Delta v_{\text{drift}} = \frac{L}{2 \cdot T_{\text{max}}}$$

$$= \frac{L}{2 \cdot (T_{\text{max}} - 2\Delta t)}. \quad (3.14)$$

To first order, this is equivalent to the following requirement:

$$2v_{\text{drift}}\Delta t - T_{\text{max}}\Delta v_{\text{drift}} = 0, \quad (3.15)$$

which can be considered as a calibration condition: all values of drift velocity and time pedestal that satisfy this relation will not affect the mean value of the residuals. This is strictly true only for small variations around the “optimal” values of $t_{\text{trig}}$ and $v_{\text{drift}}$ since larger fluctuations may affect pattern recognition.
efficiency and segment building. Lacking an external system for the track measurement, the segment is used as a reference for the computation of the residuals of the reconstructed drift distance.

The main sources of uncertainty in the determination of the time pedestal are the fluctuations in the mean value $\langle t \rangle$ and in the $\sigma$ of the fit in the different layers of a superlayer: the intrinsic statistical error, the presence of noise before the starting point of the drift time box, the finite step size of the TDC (0.78 ns), and the fact that the distribution is not perfectly described by eq. 3.4, which together limit the accuracy of $t_{\text{trig}}$ determination to about 1 ns. Further systematic uncertainties come from the uncertainty on the drift velocity, as demonstrated by eq. 3.15, therefore higher accuracy can only be achieved using a procedure for fine tuning of the time pedestal independent of the drift velocity.

An alternative approach consists in using the different dependences of $t_{\text{trig}}$ mis-calibration of the various meantimer formulas listed in [1] to calibrate the pedestal. The differences among the values of $T_{\text{max}}$ computed using different formulas can be used to measure the value of the mis-calibration $\Delta t$ once the dependence of the meantimer on the track impact angle is well under control. This would allow $t_{\text{trig}}$ to be tuned without relying on the residual distribution and therefore without depending on the calibration precision of the drift velocity. This alternative approach will be investigated in the future.

### 3.1.3 Local Reconstruction

#### 3.1.3.1 Reconstruction of the Hit Position within the Cell

The primary result of the DT local reconstruction are points in the cell volume, also called “RecHits”, which belong to the plane of the wires. These objects are built by computing the drift distance corresponding to the measured drift time.

As already discussed, two reconstruction algorithms have been developed. The first assumes a constant drift velocity over the entire cell, an acceptable approximation thanks to the good cell linearity. The second is based on a time-to-distance parameterization obtained using a GARFIELD simulation of the cell behavior, and takes into account the dependence of the cell non-linearities on the track incidence angle in the plane orthogonal to the wires and on the residual magnetic field, thus achieving better resolution. These two reconstruction algorithms are described in the following.

As discussed in Sec. 3.1.2.1, corrections to the synchronization constants due to the TOF and the signal propagation along the wire must be applied in order to achieve the best possible resolution. These corrections, as well as the parameters used as input for the cell parameterization (the track incidence angle and the magnetic field) cannot be computed for an individual digi, which
only contains information about the hit distance from the wire. For this reason an iterative reconstruction procedure is adopted:

- **first step:** reconstruction at the cell level: the left-right ambiguity is unsolved and the position of the hit along the wire is not yet determined;
- **second step:** the hits are used to build a segment within a superlayer. The position along the wires is still unknown but the left-right ambiguity of each hit is solved. Also, the track impact angle is known, and this allows recomputing the hit positions more accurately if the cell parameterization is used;
- **third step:** the segments in \( r-\phi \) and \( r-z \) projections are used to build a three-dimensional segment. The position of each hit along the wire is now fixed and can be used for a more precise estimation of the residual magnetic field, which varies along the tube. Also the estimated delays due to the TOF and the signal propagation along the wire can be refined as discussed in Sec. 3.1.2.1, so that hit positions can be further improved.

In summary, the initial reconstruction at the cell level gives the input hits used to find a segment. When a segment is built, the positions of its hits are further refined and the hits are then refitted.

In order to discard noise and pile-up signals, the reconstruction is performed only for drift times falling in a user-defined time window. Normally, the times are required to be within \(-3 \) and \(+415 \text{ ns}\), after \( t_0 \) and \( t_{\text{trig}} \) subtraction. All other digis are discarded as they cannot belong to the signal event which fired the trigger.

**Reconstruction with Constant Drift Velocity** The good uniformity of the drift field within the cell allows reconstruction of the distance from the wire associated to a certain drift time under the assumption of a constant drift velocity \( (v_{\text{drift}}) \) over the entire cell:

\[
x = v_{\text{drift}} \cdot t_{\text{drift}}.
\]  

(3.16)

The drift velocity can be estimated from data with appropriate calibration procedures, as described in Sec. 3.1.2. The same procedures also allow to estimate the error to be assigned to the reconstructed hits.

This simple reconstruction algorithm gives satisfactory results especially for tracks with small impact angles and in regions with low residual magnetic field, as in these cases the cell non-linearities are less important.

Although this method does not account for local variations of the magnetic field in the tube or for different impact angles of individual tracks, the calibration procedure determines by construction the average drift velocity which fits best the working conditions of the group of cells considered. Currently, the calibration is performed separately for each superlayer, so that the resulting drift velocity corresponds to the average conditions in each superlayer.
For this algorithm, the three-step reconstruction procedure is only used for the refinement of the synchronization constants.

**Reconstruction Using the Cell Parameterization**  The optimal cell resolution can be achieved by taking into account the small non-linearities of the cell and the dependence of the drift velocity on track parameters and magnetic field, as the impact angle of the crossing track and the residual magnetic field in the gas volume affect the drift times. These effects are considered only on average for a group of cells by the algorithm described in the previous section, where the calibration cannot account for the non-linearities and the variation of the magnetic field along the tube.

An existing parameterization [51], obtained from a GARFIELD simulation [52], has been used to implement a reconstruction algorithm which computes the drift distance by considering its dependence on the track angle in the plane orthogonal to the wires (α) and on the components of the magnetic field parallel to the wire (B_{wire}) and perpendicular to both the wire and to the drift direction (B_{norm}).

This parameterization gives the distance from the anode of tracks that would give a drift electron arrival time distribution peaked at the given time t_{drift}. We call this distance x^{t_{mode}} to indicate that it is the distance corresponding to a drift time distribution with the mode equal to t_{drift}:

\[ x^{t_{mode}} = f(t_{drift}, \alpha, B_{wire}, B_{norm}). \]  

(3.17)

The parameterization also provides the standard deviations of the fit of the drift time distribution peaked at t_{drift} with two half Gaussians, on the left and on the right of the peak, converted to distances using the average drift velocity:

\[ \sigma_p^x, \sigma_n^x = f(t_{drift}, \alpha, B_{wire}, B_{norm}). \]  

(3.18)

Actually, x^{t_{mode}} is not the relevant quantity for reconstruction, which requires the knowledge of the average distance from the wire that leads to a given t_{drift}. This is not available with the current parameterization. However, this quantity is approximately equal to the distance x^{t_{mean}} corresponding to a drift time distribution with the mean equal to t_{drift}. In the case of an ideal distribution composed of two half Gaussians, as considered by the parameterization, x^{t_{mean}} is related to x^{t_{mode}}, \sigma_p^x and \sigma_n^x by:

\[ x^{t_{mean}} = x^{t_{mode}} - (\sigma_p^x - \sigma_n^x) \sqrt{\frac{2}{\pi}}. \]  

(3.19)

This is an approximation of the actual value. A more correct result could be obtained by a dedicated GARFIELD parameterization of the mean of the
3.1 Algorithms Description and Results on Simulated Data

distribution of distances from the wire that result in a certain drift time. Such a parameterization is currently not available. The effect of this approximation is expected to be small in all the regions of the cell where the width of the distribution is slowly varying along the cell axis. This is normally the case, except in the vicinity of the anode wire. The resulting parameterization has been implemented in the official CMS reconstruction code as a function of the form:

\[
x_{\text{drift}} = f(t_{\text{drift}}, \alpha, B_{\text{wire}}, B_{\text{norm}}).
\] (3.20)

Since \(\alpha, B_{\text{wire}}\) and \(B_{\text{norm}}\) are not known at the level of the individual hit, they are introduced during the three-step reconstruction procedure previously described. For the first step, a crude estimate of the input parameters of the parameterization is used: the field value is taken at the middle of the wire and the track angles are determined assuming the track points to the nominal interaction point. The hit is then updated twice: after having been used to build a two-dimensional \(r-\phi\) or \(r-z\) segment (second step) and after having been included in a three-dimensional segment (third step).

At the second step the angle of the segment is used to update the RecHit position with eq. 3.20. In the third step the knowledge of the hit position along the wire is used to better evaluate the magnetic field and \(x_{\text{drift}}\) is computed again. The knowledge of the three-dimensional position of the hit also allows refining the synchronization.

The values of the two sigmas, \(\sigma_p^x(t)\) and \(\sigma_n^x(t)\), are not related to the actual uncertainty to be assigned to the measurement, as they represent the width of the drift electron arrival time distributions translated into a distance. The actual uncertainties on the reconstructed hits are estimated from the residual distributions obtained by subtracting the distances from the wire of RecHits and simulated hits. Gaussian fits have been performed and the corresponding sigmas recorded separately for \(r-\phi\) and \(r-z\) superlayers for each reconstruction step. In the case of \(r-z\) superlayers, different uncertainties are assigned to the different wheels, as track impact angles in the plane orthogonal to the wires are larger for the external wheels. The uncertainty values for the different cases are reported in Table 3.1. At the third reconstruction step the uncertainty on the reconstructed distance is of the order of 200 \(\mu\text{m}\) for all the superlayer types in the different wheels. In this way, no dependence of the error on the hit position within the cell is taken into account.

**Performance of the Hit Reconstruction** The goal of this section is to show the algorithmic performance of the hit reconstruction on simulated data. The reconstruction is performed using the \textsc{garfield} parameterization. The known exact \(t_{\text{trig}}\) offsets applied during the simulation are used for the synchronization. It should be noted that, while this choice allows decoupling the study of the
Table 3.1: Uncertainties (in $\mu m$) assigned to one-dimensional RecHits reconstructed using the cell parameterization algorithm at the various reconstruction steps, for different types of superlayers and wheel positions. These uncertainties are obtained from a Gaussian fit of the residual distribution of the reconstructed drift distance on simulated events.

<table>
<thead>
<tr>
<th>Superlayer type</th>
<th>$r-$</th>
<th>$r-$</th>
<th>Wheel 0</th>
<th>$r-$</th>
<th>Wheel $\pm 1$</th>
<th>$r-$</th>
<th>Wheel $\pm 2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1</td>
<td>237</td>
<td>250</td>
<td>271</td>
<td>308</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step 2</td>
<td>231</td>
<td>250</td>
<td>271</td>
<td>305</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step 3</td>
<td>207</td>
<td>196</td>
<td>210</td>
<td>228</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

reconstruction algorithm from the accuracy of the calibration procedure, the true cell resolution includes an additional contribution due to the accuracy in the computation of the $t_0$ and $t_{\text{trig}}$ delays.

The simulated sample used for this study consists of $10^5$ single muons generated with a flat $p_T$ spectrum in the range 10 - 100 GeV, with $|\eta| < 1.3$.

Figure 3.12: Residuals between the reconstructed and the simulated hit distances from the wire. The 3 plots refer to the first (left), second (center) and third (right) reconstruction steps of the cell parameterization algorithm in $r-$ superlayers.

The plots in Fig. 3.12 show the resolution on the (unsigned) distance from the wire for hits reconstructed in the DT cells of $r-$ superlayers. The distributions are Gaussian, with the mean values and sigmas given in Table 3.2 separately for $r-$ superlayers and for the $r-$ superlayers in the different wheels.

The width of the residuals grows towards the outermost wheels in the $r-$ superlayers. This is due to the impact angle of muons, which increases with pseudorapidity, enhancing the effect of the cell non-linearities. This effect is less
3.1 Algorithms Description and Results on Simulated Data

Table 3.2: Residuals between the reconstructed and the simulated hit distances from the wire. The mean value (μm) and the sigma (μm) of the Gaussian fit are reported for the three reconstruction steps performed with the cell parameterization algorithm, in r-φ and r-z superlayers.

<table>
<thead>
<tr>
<th>Superl. type</th>
<th>r-φ mean</th>
<th>σ</th>
<th>r-z, Wheel 0 mean</th>
<th>σ</th>
<th>r-z, Wheel ±1 mean</th>
<th>σ</th>
<th>r-z, Wheel ±2 mean</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1</td>
<td>-23.6 ± 0.1</td>
<td>238</td>
<td>6 ± 0.5</td>
<td>265</td>
<td>6 ± 0.4</td>
<td>281</td>
<td>-7 ± 0.5</td>
<td>314</td>
</tr>
<tr>
<td>Step 2</td>
<td>9.8 ± 0.1</td>
<td>232</td>
<td>7 ± 0.5</td>
<td>264</td>
<td>7 ± 0.4</td>
<td>281</td>
<td>-4 ± 0.5</td>
<td>315</td>
</tr>
<tr>
<td>Step 3</td>
<td>-2.4 ± 0.1</td>
<td>210</td>
<td>-2.7 ± 0.4</td>
<td>204</td>
<td>-1.6 ± 0.5</td>
<td>219</td>
<td>-7 ± 0.4</td>
<td>231</td>
</tr>
</tbody>
</table>

pronounced at the second and third reconstruction steps where the knowledge of the segment angle is used as input in the parameterization. The final resolution is about 200 μm in all the chambers.

The tails of the distributions of the residuals are non-Gaussian and asymmetric as shown in Fig. 3.13, where the residuals after the first reconstruction step in r-φ superlayers are plotted. The long tail towards negative values is

Figure 3.13: Residuals between the reconstructed and the simulated hit distances from the wire. The plot refers to the first reconstruction step performed with the cell parameterization algorithm, in r-φ superlayers. Note the extended range with respect to Fig. 3.12.

due to the delta-rays and secondary hits from electromagnetic debris. Due to
the dead time of the TDC, only the hits giving drift times smaller than the one from the primary electron can be detected. The distribution drops sharply around 8.1 mm which, considering an average drift velocity of about 54 μm/ns, corresponds to the dead time of 150 ns set in the simulation.

The uncertainty assignment on the reconstructed position plays an important role in the segment reconstruction since the pattern recognition is based on a quality selection exploiting the $\chi^2$ of the linear fit.

The shape of the pull distributions is not perfectly Gaussian since the assignment of an uniform uncertainty along the whole cell is not the ideal choice due to the presence of critical regions, like the one close to the anode, where the drift time distribution is affected by strong non-linearities. The widths of the pulls are however very close to unity in all the cases.

A comparison of the reconstruction algorithm with constant drift velocity with the algorithm based on the GARFIELD parameterization shows the effect of cell non-linearities. The plots in Fig. 3.14 show the residuals between the reconstructed and simulated distance from the wire as a function of the simulated one. They refer to the worst situation, the first reconstruction step in $r$-$z$ super-layers of wheels $+2$ and $-2$, where the large impact angle and the non-negligible magnetic field enhance the effect of the non-linearities in the drift of electrons. The plot on the left shows the results obtained using the cell parameterization while the one on the right shows the performance of the constant drift velocity method. In the first case, the effect of the non-linearities is below 100 μm also in the most problematic region, close to the anode. The situation is completely different in the plot on the right where the average value of the residuals can vary by more than 150 μm when moving by a few millimeters away from the anode.

### 3.1.3.2 Segment Reconstruction

Under ideal circumstances, a muon coming from the interaction region gives twelve hits in a chamber, one in each layer. In practice some hits may be missing due to inefficiencies; tracks at large angle may give rise to two hits in adjacent cells of the same layer and there may be additional hits due to background from electromagnetic debris, neutrons and noise. The purpose of the segment building procedure is twofold: first, to identify which of the reconstructed hits stem from the muon track to reduce the combinatorics; and second, to resolve the left-right ambiguity for each hit. Moreover, the combined use of many hits also allows an increase in the spatial resolution for individual hits, as the segment reconstruction provides a precise determination of the track impact angle and of the hit position along the wire, which can be used to refine the computation of the drift distance (as explained in Sec. 3.1.3.1).
3.1 Algorithms Description and Results on Simulated Data

Figure 3.14: Residuals between the reconstructed and simulated distance from the wire as a function of the simulated one. The plots are referred to hits reconstructed using the cell parameterization algorithm (left) and the constant drift velocity algorithm (right) in $r$-$z$ superlayers of wheels $\pm 2$.

The segment reconstruction acts in each chamber on the $r$-$\phi$ and $r$-$z$ projections independently: only at the end of the procedure the two projections are combined and a three-dimensional segment is built$^2$.

The reconstruction in each projection is an exercise of pattern recognition and fitting, with the complication of left-right ambiguity. A linear fitting model, given the hit resolution and the small height of a chamber, is adequate. The reconstruction is performed in three steps:

- segment candidates are built from sets of aligned hits;
- the best segments among those sharing hits are selected, solving conflicts and suppressing ghosts;
- the position of the used hits is then updated using the information from the segment (as explained in Sec. 3.1.3.1) and the segments themselves are eventually re-fitted.

Building segment candidates The first step begins by selecting pairs of hits in different layers, starting from the most far away layers. For each pair the reconstruction of a segment candidate is then attempted.

A pair is kept if the angle of the corresponding proto-segment is compatible with a track pointing to the nominal interaction point within a given tolerance,

$^2$In the CMS jargon, a segment in one projection is referred to as “2D-segment”, meaning that it provides 2 measurements: the position and the track angle in one projection. Likewise, a segment in space, built using two projections, is called “4D-segment”, since it provides 4 parameters (2 positions and 2 angles).
usually set to 0.1 rad for the $r$-$z$ projection and 1.0 rad for the $r$-$\phi$ one, since this is the projection where the track bending occurs. These constraints can be switched off for the reconstruction of cosmic muons. As each hit has a left-right ambiguity, both hypotheses are considered, provided they fulfill the above condition.

For each pair, additional hits are searched for in all layers. Hits are considered when distance from the extrapolated segment is smaller than 10 times the position error, as estimated by the hit-building algorithm. It is possible that both the left and the right hypotheses are compatible with the segment. In this case, both candidates are retained and the ambiguity is solved later. Also, a muon can cross the I-beam separating two cells generating a signal in both. In this case, both hits are considered for that layer, in order to avoid any bias.

Once the pattern recognition is completed, each collection of hits is fitted. For each seed (i.e., pair of hits) only the segment candidate with the maximum number of hits and the minimum $\chi^2$ is retained; all others are rejected. Finally, a quality criterion is applied, requiring the number of hits $\geq 3$ and the reduced $\chi^2 < 20$ for all the candidates.

This algorithm is applied directly to the $r$-$z$ superlayer in each chamber. It can also be applied to individual $r$-$\phi$ superlayers, and the resulting segments are useful for commissioning and studies of superlayer performances. However, for the purpose of track fitting it is more convenient to consider the two $r$-$\phi$ superlayers in a chamber together. The procedure described above is therefore applied to the eight $r$-$\phi$ layers of each chamber and the resulting segments are then used for building three-dimensional segments, as described in the following.

In case of showering, the occupancy in the chamber can be extremely high. Pattern recognition is critical in this case, first because hits from secondary particles may mask the true muon hits if they happen to be closer to the wire, due to the cell dead time; and second because large occupancies lead to an explosion of the combinatorics which can deteriorate the performance of the pattern recognition. For this reason the procedure described above is not attempted if the number of hits in a given projection is larger than a programmable number (default is 50). In this case, different methods to provide a measurement to be used in the track fit have to be applied and are under study.

**Segment selection**  The pattern recognition described above produces a set of segment candidates. A consistency check is performed in order to test whether two candidates use different left-right hypotheses for the same hit. In this case, the conflicting hit is removed from the worse of the two segments, where quality is defined, as above, by the maximum number of hits and the minimum $\chi^2$.

Specific incidence angles can result in hit patterns for which two segment candidates share all their hits, with different left-right hypotheses for each one.
The two candidates have in this case the same quality. In p–p collisions, the choice is implicit in the request of compatibility with the nominal interaction point described previously. When this requirement is removed, as for the reconstruction of cosmic muons, two options are available: either retaining both candidates, thus leaving the selection of the best segment to the muon track fit algorithm, or choosing the candidate with the smallest angle (with respect to the vertical to the chamber) among the conflicting ones, which in specific operating conditions is most likely to be the correct choice.

The segments are allowed to share non-conflicting hits up to a given number: the default is two. If more are present, the worst candidate is rejected. If two segments share some hits, they are required to have a minimum number of non-shared hits, in order to further reduce the number of short ghost segments. The minimum number of non-shared hits is programmable as well and the default is two.

The hits from the remaining candidates are updated (“second step” mentioned in Sec. 3.1.3.1), taking into account the incidence angle reconstructed by the segment. The segment linear fit is then recomputed using the updated hits.

**Matching of the two projections** Up to this point, the \( r \)-\( \phi \) and \( r \)-\( z \) projections are handled independently. As the two projections are orthogonal, a segment in one projection cannot be used to validate a segment in the other: all combinations of segments from the two projections are kept.

The additional knowledge of the hit position along the wire is used to update the \( x \) position in the cells (“third step” described in Sec. 3.1.3.1) before performing the final fit of the segment. The result is a segment inside a chamber suitable for use in the track reconstruction.

**Performance of the Segment Reconstruction** Position and angle residuals for 2D segments on a single superlayer are shown in Fig. 3.15 and 3.16 for \( r \)-\( \phi \) and \( r \)-\( z \) projections, respectively. The position resolutions are about 115 \( \mu \text{m} \) and 140 \( \mu \text{m} \) in the two cases. The worse resolution on the \( r \)-\( z \) projection is mainly due to the higher impact angle of the muon in these superlayers. The resolution on the angle is about 8 mrad for both projections. It is worth to stress that, in the \( r \)-\( \phi \) projection, segments built using both \( r \)-\( \phi \) superlayers are used.

The three-dimensional segments built by combining the \( r \)-\( \phi \) and \( r \)-\( z \) projections are the basic ingredient for the track fit. Figure 3.17 shows the residuals on the bending coordinate \( x \) and on the non-bending coordinate \( y \), which are the components measured by the \( r \)-\( \phi \) and \( r \)-\( z \) superlayers, respectively. The resolution improvement with respect to Fig. 3.15 is due, in the case of \( x \), to the fact that the two \( r \)-\( \phi \) superlayers are now used together, thus doubling the
Figure 3.15: Residuals on the position (left) and angle (right) measured by two-dimensional segments in $r$-$\phi$ superlayers.

Figure 3.16: Residuals on the position (left) and angle (right) measured by two-dimensional segments in $r$-$z$ superlayers.

number of measurement planes and increasing the lever arm from $\sim 4$ cm to $\sim 25$ cm. Also, for both projections the single hit resolution is better due to the additional knowledge of the position of the hit along the wire. In the bending plane, with a resolution of about 240 $\mu$m for the single one-dimensional hit (see Sec. 3.1.3.1), it is possible to achieve a precision of about 90 $\mu$m. Moreover, spurious hits are rejected and the combinatorics for the next reconstruction steps is reduced.

The resolution on the non-bending coordinate is about 120 $\mu$m. The most accurate determination of a segment coordinate is obtained at a plane corresponding to the center of gravity of the hits, weighted by their errors. This
Figure 3.17: Residuals on the position of three-dimensional segments. Left: residual on \( x \) (bending coordinate), given at the middle plane of the two \( r-\phi \) superlayers. Right: residual on \( y \) (non-bending coordinate) given at the middle plane of the \( r-z \) superlayer.

corresponds approximately to the middle plane of the chamber in the case of the \( r-\phi \) projection, and the middle plane of the \( r-z \) superlayer for the \( r-z \) projection. These two planes do not coincide, as can be observed in Fig. 3.3. However, it is often convenient to give the position of the segment as a single three-dimensional point, and in this case both coordinates have to be given at the same plane. The middle plane of the chamber is chosen, in order to favor the bending coordinate, while the non-bending coordinate has to be extrapolated from the position measured on the middle plane of the \( r-z \) superlayer. Therefore in the 3D position of the segment, the residual on the \( y \) coordinate is degraded to about 530 \( \mu \)m (the full error matrix, including the correlations terms between positions and angles, is available). If a precise estimate of the position of the segment in the non-bending coordinate is required, it is recommended to use the position of the \( r-z \) segment projection defined in the \( r-z \) superlayer frame rather than the \( y \) coordinate of the 3D segment position.

The resolution on the direction of the reconstructed segments is shown in Fig. 3.18. An angular resolution of about 0.7 mrad is achieved in the \( r-\phi \) projection, thanks to the presence of two superlayers with a long lever arm. On the other projection (\( r-z \)), the resolution is about 6 mrad.

The large non-Gaussian tails of the distribution are mainly due to the presence of energetic secondary hits which, crossing different layers, can affect the pattern recognition.
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Figure 3.18: Residuals on the angles measured by three-dimensional segments in the $r$-$\phi$ (left) and $r$-$z$ (right) projections.

The pulls on the segment angle and position have been also studied: they are well centered at zero and with a standard deviation close to unity for both the types of superlayer.

3.1.3.3 Conclusions

We have summarized the algorithms currently implemented in the CMS software for the local reconstruction in the DT system of CMS. Concerning the resolution, the GARFIELD parameterization used in the reconstruction of the cell hits gives better results with respect to the constant drift velocity, especially in the most critical regions, thanks to the modeling of the cell non-linearities. This has been also tested on test-beam data, as described in [57] and [58].

However, the reconstruction algorithm based on the parameterization of the cell behavior is intrinsically more complex than the one using a constant drift velocity. This should suggest caution in exploiting it at the start-up of LHC. The very simple algorithm with constant drift velocity can be instead used as a first step on real data; afterwards, when a deep understanding of the DT behavior will be reached, the usage of the parameterization will be advisable in order to achieve the best resolution.

Moreover, the parameterization of the cell is still open to further improvements. In fact, the parameterization currently used was not designed for the reconstruction: a more detailed treatment would require a dedicated GARFIELD simulation. In particular the simulation should be used to build the distribution of the distances corresponding to a certain drift time, extracting from that a parameterization of the average drift-distance and of the width of the distribution.
which would allow parameterizing also the error associated to the reconstructed hit.

As far as segment building is concerned, the problem of high occupancy in the presence of muon showering should be addressed with a dedicated reconstruction not based on the current combinatorial pattern recognition. A possible solution which is under study is a clustering algorithm of the hits in the chamber; this would allow skipping the segment building when the hit multiplicity is too high.

3.2 Effects on Stand-alone Muon Reconstruction

In Sections 3.1.2 and 3.1.3 the effects of an imperfect calibration of the time pedestals on the local reconstruction are described (Figures 3.7 and 3.8) and a comparison of the single hit resolution using the cell parameterization algorithm or using a constant drift velocity is shown (Fig. 3.14). It is worth to study what are the effects of these issues (calibration and local reconstruction algorithm) on higher-level variables, like the resolution of the stand-alone muon reconstruction described in Sec. 2.3.1.

For this purpose 10000 events of $Z \rightarrow \mu \mu$, corresponding to a little less of 10 pb$^{-1}$ of integrated luminosity, have been reconstructed in different conditions:

- ideal calibration and reconstruction with the cell parameterization algorithm;
- 5 ns and 10 ns Gaussian smearing of the time pedestals and reconstruction with the cell parameterization algorithm;
- realistic calibration of the time pedestals (with a few ns uncertainty) and reconstruction with constant drift velocity calibrated superlayer by superlayer as explained in Sec. 3.1.2.2.

The scenario with 10 ns smearing of the time pedestals is a reasonable model of the calibration conditions in cosmic data because of the random arrival time of cosmic muons, as discussed in Sec. 3.3. The last scenario, with time pedestal and drift velocity realistic calibration, corresponds to the precision reachable with 1 pb$^{-1}$ of data.

In Fig. 3.19 the angular resolution, the resolution on the transverse momentum and the reconstructed di-muon mass distribution with stand-alone muons are shown. The resolution is computed with respect to simulated tracks with $\Delta R < 0.1$ matching. Only stand-alone muons with $p_T > 3$ GeV and $|\eta| < 2.4$ are considered.

The miscalibration does not affect appreciably the resolution: compatible results are obtained in all the scenarios by fitting the bulk ($\pm 0.2$ range) of the
Figure 3.19: Resolution on the polar angle (up, left), the azimuthal angle (up, right), the transverse momentum (bottom, left) and di-muon invariant mass distribution (bottom, right) computed with 10000 $Z \rightarrow \mu\mu$ events in several calibration scenarios.

Table 3.3: Fraction of lost events under the $Z$ peak (between 80 GeV and 100 GeV) for several calibration scenarios. The number of events in case of ideal calibration and reconstruction with the cell parameterization algorithm is taken as reference to compute the lost fraction.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Lost events</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 ns smearing time pedestals</td>
<td>0.4% ± 0.1%</td>
</tr>
<tr>
<td>10 ns smearing time pedestals</td>
<td>4.9% ± 0.3%</td>
</tr>
<tr>
<td>1 pb$^{-1}$ scenario</td>
<td>1.0% ± 0.2%</td>
</tr>
</tbody>
</table>
3.3 Commissioning with Cosmic Data

The DT chambers, during their full path from the production sites up to their final allocation in the CMS experiment, have been deeply and repeatedly tested to ensure they are in the best possible working condition and to produce detailed and accurate reference data about their status and quality.

Beside dedicated test beam runs, taken on prototypes and on final detectors prior and during chamber construction [56, 59, 60, 61, 62], chamber commissioning was performed with cosmic data through the following phases:

- gas tightness, efficiency, dead channels, noisy channels and resolution have been tested at production sites with final front-end electronics and temporary trigger and read-out electronics;
- the same tests have been repeated after full dressing with final on-board trigger and read-out electronics (minicrates) and coupling to RPC and survey;
- full operational check was performed after installation in surface with temporary cabling and local data acquisition system;
- Magnet Test and Cosmic Challenge (MTCC);
- full commissioning of equipped wheels with all chambers and final CMS DAQ, HV, LV, Detector Control System and cabling in the cavern;
- Global Run, with full integration of DT system in CMS trigger and data acquisition chain.

In the following some results regarding the last three steps of the DT commissioning will be shown.

The calibration and reconstruction procedures presented in Sections 3.1.2 and 3.1.3 have been optimized for bunched muons in p–p collisions. Particular care has been taken in their development to provide the flexibility needed to run in different conditions. Nevertheless the calibration results obtained with cosmic data will not be directly applicable to p–p collision data.

The data synchronization and the resolution can be affected by the bunch crossing (BX) assignment. Cosmic muons have in fact a flat arrival time distribution while the trigger electronics is designed for bunched muons: the BX assignment introduces therefore a smearing of about $25/\sqrt{12}$ ns on the time measurement, which corresponds to a smearing of about 400 $\mu$m on the reso-
lution. Moreover the $t_{\text{trig}}$ estimation and the drift velocity determination can be influenced by the peculiar impact angle distribution of cosmic muons, which also implies different TOF with respect to bunched muons. Also the pattern recognition in the reconstruction procedure must be adapted to match with the particular pattern of cosmic muons.

3.3.1 Magnet Test and Cosmic Challenge (MTCC)

The test of the CMS magnet in summer 2006 provided a unique opportunity to study the behavior of the CMS detector in more realistic conditions. Between June and November 2006 the return yoke, and thus the entire detector, was closed to allow the operation of the magnet. During this period a large amount of cosmic data (about 230 M of events) has been registered using a subset of the CMS sub-detectors, with and without magnetic field.

For the muon system three barrel sectors (wheel 2 sectors 10 and 11, wheel 1 sector 10) and a 60 degrees slice of the adjacent endcap (ME1, ME2 and ME3 of the first three planes of the positive endcap), instrumented with final electronics, were operated. This accounts for 14 DT chambers (corresponding to about 10000 DT channels), 21 RPC chambers and 36 CSC chambers and this corresponds to about 5% of the muon barrel system and 17% of the positive endcap. Both the read-out and the trigger system were tested.

The MTCC has been performed on surface (510 m on the sea level) ensuring a cosmic rate of about 15 kHz on the positive $z$-half of CMS, which can be compared to the expected muon rate of about 40 kHz at the LHC startup ($10^{32}$ cm$^{-2}$s$^{-1}$).

The MTCC was mainly a hardware and software integration test where the muon system has been requested to work as a whole. The performances of the detector have been analyzed under different trigger conditions and magnetic field values; the various software components have been also deeply tested, particularly for what concern the interplay with databases and the integration with DAQ.

3.3.1.1 Dependence of the Calibration Constants on Running Conditions

The MTCC has been an important test for the official DT calibration algorithms in such a complex environment: the calibration procedure has been attempted for the first time for many chambers at once, with different values of magnetic field and on events triggered from different sub-detectors. The dependence of the DT calibration constants on these running conditions has been studied and the results are presented in the following.
Variation with the trigger source  The calibration of the time pedestals has been studied separately for each muon trigger source (DT, RPC and CSC). An exclusive definition of the trigger is used: events triggered by more than one sub-detector are discarded in order to disentangle the effects of each trigger source. The results obtained with such definition are compared with those obtained using an inclusive trigger selection showing that no bias is introduced.

In Fig. 3.20 the results of the $t_{\text{trig}}$ calibration are shown for a global run without magnetic field. Considering all the main sources of uncertainty in the determination of the time pedestal, the limit on the accuracy of the $t_{\text{trig}}$ determination should be of the order of 1 ns (as discussed in Sec. 3.1.2.1).

Figure 3.20: Values of $\langle t \rangle$ (above) and distribution of $\sigma$ (below) from the fit of the time box rising edge for each DT superlayer and for different trigger source.
Regardless of the trigger source, the inflexion point of the time box rising edge increases from MB1 to MB4 in each sector because of the TOF between the MB stations. Moreover the three sectors show a different relative synchronization.

The time pedestals are very similar in case of DT or RPC trigger: the differences are below 6 ns. When the trigger comes from CSC, instead, a different pattern is observed: in wheel 2 the results are similar to the other trigger sources while in wheel 1 there are large differences (between 5 and 30 ns). The angular distribution of the tracks passing through the CSC and each DT chamber in wheel 1 has been studied and the relative TOF (up to about 25 ns) can not completely explain the observed $t_{\text{trig}}$ differences.

These large differences of the time pedestals of wheel 1 in DT and CSC triggered events can be due to the BX assignment: the trigger needs to assign the muon to a given BX while the cosmic muons are not synchronous with the trigger clock. Because of the large TOF between the CSC’s and the wheel 1 of the DT’s, the BX chosen by the CSC trigger is the previous one with respect to the one which the DT’s would choose and this fact causes an overestimation of the $t_{\text{trig}}$.

This problem will not be present during p–p collisions. In fact in this case the muons are bunched, i.e., they are produced synchronously with the trigger clock, and the TOF from the interaction point to a given station is constant for all the muons. Therefore the different sub-detectors can be synchronized taking into account the TOF so that all of them should assign the muon to the same BX.

The flat arrival time distribution of cosmic muons introduces a smearing in the drift time measurement proportional to the trigger window. During the MTCC the time coincidence between the different chambers in the trigger did not consider the TOF between them. Hence the effective time trigger window was smaller than 25 ns because all the signals released by the muons in the different chambers had to fall in the same trigger clock window. For this reason the effective RPC trigger window was smaller than the DT one and therefore the $\sigma$ values are on average about 1.5 ns smaller in the RPC triggered events with respect to those triggered by the DT’s.

Finally the $\sigma$ values for CSC are really large because of the additional smearing due to the large TOF between CSC’s and DT’s and the BX assignment effect previously described.

**Variation with the magnetic field** As expected, no dependence on the magnetic field is observed in the $t_{\text{trig}}$ values, while the residual field can influence the $\sigma$ and the drift velocity. The results for these two calibration parameters are shown in Fig. 3.21 for two DT local runs with different magnetic field conditions.
When the solenoid delivers 4 T, the residual magnetic field distort the electric field lines in the cell (as shown in Fig. 3.1). This non-linearity introduces an additional smearing in the drift time distribution which increases the $\sigma$ values on average of about 1 ns.

The drift velocity variation induced by the magnetic field are at most of the order of 0.5% in all the superlayers with the exception of the MB1 chambers in wheel 2 where the residual field can be up to 0.8 T, as shown in Fig. 2.11, inducing a drift velocity variation of some percents.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.21}
\caption{Distributions of $\sigma$ from the fit of the time box rising edge (up) and $v_{\text{drift}}$ values (bottom) for each DT superlayer with and without magnetic field.}
\end{figure}
3.3.1.2 Experience with the DT Local Reconstruction

The MTCC provided a unique opportunity to test the reconstruction algorithms for different magnetic field strengths. The typical example shown in Figure 3.22 displays the cells which yielded a signal (green boxes) along with the chamber segments (red line) for each of the four stations in a given sector.

![Figure 3.22: Display of a cosmic muon in the barrel system with 4 T magnetic field. The segments from local reconstruction in each station are shown.](image)

To efficiently reconstruct cosmic ray tracks, modifications of the algorithms were necessary, which are optimized for muons from bunched p–p collisions. The default CMS segment reconstruction includes vertex constraints for $r-\phi$ as well as $r-z$ superlayers. These have been disabled so that all possible angles of the segments can be measured, given that the trigger has accepted the event. As a consequence, in some topologies the left-right ambiguity can no longer be resolved uniquely simply by using the segment candidate with the smallest $\chi^2$ (see Fig. 3.23). This leads to segments with unphysical angles even larger than the trigger acceptance, in addition to the candidate corresponding to the true path of the cosmic muon. During the MTCC analysis a modification was implemented in order to select the right candidate during local reconstruction. The segment is chosen which has the smaller angle with respect to the direction orthogonal to the chamber thus favoring tracks which are closer to the vertical as it is realistic for cosmic muons.

The hit multiplicity of well reconstructed segments should be 12 (one hit in each layer of the chamber). The hit multiplicity of the segments in MTCC data showed an excess of three hit segments when comparing MTCC data and
simulated data from p–p collisions. These low-quality segments had flat angular distribution, their $\chi^2$ peaked at low values and they appeared typically in events with more than one reconstructed segment in the same chamber. The presence of this bad quality segments was due to the fact that the usual selection criterion (number of hits $\geq 3$ and reduced $\chi^2 < 20$) is too loose on cosmic data, where the intrinsic hit resolution used for the pattern recognition has to be large because of the flat arrival time distribution of the cosmic muons. Therefore it is rather easy for three hits to be sufficiently aligned to fulfill the loose track criterion, in particular since the pattern recognition accepts hits to be shared by several segments. Such fake segments can be reduced by requiring that any segment must have at least two unshared hits. This new requirement has been implemented in the software.

After these modifications for cosmic muons, the DT reconstruction algorithms performed well on the MTCC data. The average efficiency for track reconstruction in MTCC data has been measured to be $\sim 97\%$ for triggered events.

### 3.3.2 DT Local and Global Commissioning

During the DT commissioning two set-up of data taking were available: in the so called “local runs” the DT trigger and read-out electronics work in a stand-alone way with private DAQ, while in the so called “global runs” (started from November 2007 and became more and more frequent with gradually increased complexity) the CMS detector is requested to work as a whole with global trigger and central DAQ.

Starting from Autumn 2006 the integration of the DT system has been also increased. Before the MTCC, during the assembling in surface, a long stage of single chamber commissioning has taken place. The following integration
step was the sector commissioning, where each sector was tested at once. Then in the wheel commissioning all the sectors inside a wheel were triggering and taking data at the same time. Finally all the wheels were integrated.

This gradual integration was not only an increase in size (more sub-detectors means obviously higher rate and bigger data size) but also an increase in complexity which requires, for instance, a careful synchronization of the various sub-detector pieces.

### 3.3.2.1 Time Pedestal Calibration

As explained in Sec. 3.1.2.1, the time pedestal includes the trigger latency, thus it depends on the trigger configuration. In Fig. 3.24 the comparison of the time pedestals for a given wheel computed in various local runs of sector commissioning with “default cosmic trigger” and with “technical trigger” is shown.

The DT trigger inside each chamber search for a high quality segment in $r$-$\phi$ superlayers and at least one hit in the $r$-$z$ superlayer, then the default cosmic trigger ask for a coincidence of at least two chambers inside the sector, while the technical trigger is a logic OR of the chambers inside the sector. Actually, the default cosmic trigger is a modification of the trigger configuration foreseen for bunched muons in p-p collisions. In this case an electronic module, the DT Track Finder (DTTF), is in charge of extrapolating the trigger chamber segment to the other chambers of the same sector and of searching for another chamber segment inside the extrapolated region. Afterwards, the Wedge Sorter boards have the task of sorting by $p_T$ the muon tracks found by the Track Finder system. Finally the Barrel Sorter board chooses the best four track candidates to be sent to the global muon trigger. As a consequence, the electronic chain of the default cosmic trigger is much more complex than the one for technical trigger and hence its latency is larger of about 27 - 28 BX’s.

Each sector of Fig. 3.24 was tested in a separated local run. The $t_{\text{trig}}$ values of the chambers inside the same sector are equal because they were synchronized among them, while the $t_{\text{trig}}$ values of the chambers in different sectors are different because the various sectors were not yet synchronized among them.

The synchronization between different sectors has been done during the wheel commissioning exploiting muon tracks which crossed two sectors. The trigger latency has been changed to maximize the trigger coincidences between adjacent sectors or between two opposite sectors (which are separated by a TOF of about 6 ns). In Fig. 3.25 the time pedestal values before and after this synchronization procedure are shown.

Finally in Fig. 3.26 the time pedestal values computed in a wheel commissioning local run and in a global run are compared. A fixed shift can be seen
between sectors. Because in the second case the trigger latency includes also the trigger chain of technical (SL1)
3.3.2.2 Test-pulses, Noise and Dead Channels

During dedicated runs test-pulses are injected inside the detector and they are read back. This allows, through the calibration procedure described in Sec. 3.1.2.1, to inter-synchronize all the channels inside each chamber.

As you can see in Fig. 3.27, test-pulses are usually injected in several groups of cells in all the layers at once: adjacent staggered cells are illuminated in order to simulate a track pattern to activate the trigger. The number of cells illuminated at once in each layer, the pulses rate and the number of signals injected before moving to the next cell are configurable.

In Fig. 3.28 the relative difference on the signal propagation time of each channel path (i.e., the $t_0$ values) is shown for all the chambers in a given sector. The steps inside each superlayer correspond to different Read-Out Boards (ROB’s, see Sec. 2.1.2.1), the spread inside each ROB is usually less than 1 ns.

Exploiting the test-pulse runs, the dead channels can be identified. The wires without the test-pulse peak (also in presence of uniformly distributed noise) are defined as dead. Only 14 dead channels are found in the full DT detector (less than 0.01%).

The noise can be studied in three different configuration:

- during cosmic data taking, looking at the digis with time smaller than the time pedestal which fall in the region before the time box (the region after the time box is not considered because is populated by after-pulses);
3.3 Commissioning with Cosmic Data

Figure 3.27: Catch in the $r$-$\phi$ plane of a single test-pulse event from the official CMS visualization software IGUANA [63].

- during dedicated random trigger runs;
- during test-pulse run, looking at the noise far away from the test-pulse peak;

In Fig. 3.29 the digi time distribution in all this cases is shown.

An extensive study has been performed on the random trigger data with read-out threshold at 20 mV: between 30 and 50 wires per wheel ($\sim 0.15\%$) have a noise rate between 100 Hz and 500 Hz and between 80 and 100 wires per wheel ($\sim 0.3\%)$ can be defined as noisy (rate > 500 Hz). However the noise rate depends strongly on the data taking conditions (grounding, low voltage power supply, interplay with other CMS detectors). These conditions changed quite frequently during the commissioning with Local and Global Runs before the final CMS closure.
Figure 3.28: $t_0$ values in sector 1 of wheel 0 computed from a test pulse run.
Figure 3.29: The digi time distribution for a cosmic run (above), a random trigger run (below, left) and a test-pulse run (below, right). In the first case the digis of all the chambers are considered (6 sectors were switched on in this particular run). The last plot refers to a single wire: the digis uniformly distributed are due to noise, the first peak is an instrumental noise due to the enabling of the channel mask and the last peak is due to the test-pulses. In the random trigger case a larger TDC time window is used (30000 TDC counts against the usual window of 7000 TDC counts).
Chapter 4

Muon Commissioning with Standard Model Measurements

Muons play a key role in Higgs search (as explained in Chapter 5) and new physics search (e.g., $Z' \rightarrow \mu \mu$). However, before any discovery can be claimed, a well-founded control of the detector and reconstruction performances is needed: the muon momentum scale, the muon momentum resolution and the muon online and offline selection efficiencies must be measured from data exploiting well-known processes like $Z \rightarrow \mu \mu$ or also, for the muon scale calibration, low di-muon mass resonances ($J/\psi$ and $\Upsilon$).

After an introduction about these SM processes at LHC (Sec. 4.1), an algorithm is presented to exploit them in order to measure from data the muon resolution and to correct the muon momentum scale (Sec. 4.2). Finally the effects of such calibration procedure on the systematics of the $Z$ cross section measurement are described in Sec. 4.3.

4.1 First Measurements with Muons

Thanks to the precise knowledge of the $Z$ and $W$ production processes and thanks to their huge statistics at LHC, they will be widely exploited as “standard candles”, as explained in Sec. 4.1.1.

On the other side di-muon quarkonia resonances ($J/\psi$ and $\Upsilon$) have well-known masses, therefore can be used to calibrate the muon momentum scale at low momenta, but the physics involved in quarkonia production is not yet well known. In Sec. 4.1.2 the main features of the heavy quarkonia production at LHC and the physics interest of its study are shown. As reference, a brief review of the CMS potential on the $J/\psi \rightarrow \mu \mu$ channel is presented.
4.1.1 W and Z Production

The cross sections of W and Z bosons production at LHC will be huge: \( \sigma(pp \rightarrow W \rightarrow l\nu) \sim 20 \text{ nb} \), \( \sigma(pp \rightarrow Z \rightarrow l^+l^-) \sim 2 \text{ nb} \). Moreover the W and Z decay processes have been measured with high accuracy in previous experiments. Thus the W and Z bosons will play a key role during the first data taking at LHC allowing to test the detector performances and to tune the Monte Carlo (MC) generators.

The processes involving electroweak bosons will be suitable for calibrating the Electromagnetic Calorimeter, for aligning the muon system and the inner tracker and for calibrating the track reconstruction. The study of Z and W events will also improve the knowledge of the Parton Distribution Functions (PDFs) and it will provide a raw luminosity monitoring. These analyses hold the key for all the subsequent physics searches because they provide the way to control the main experimental and theoretical systematics at LHC.

It should be noted that W and Z inclusive production are also interesting processes at LHC as test of the Standard Model at an unprecedented scale and as backgrounds to new physics searches.

For all these reasons, the W and Z cross section evaluation will be one of the first measurements performed at the LHC start-up. In Sec. 4.1.1.1 the \( Z \rightarrow \mu\mu \) case is considered: a brief description of the measurement strategy is presented and the main theoretical and experimental systematics are addressed.

4.1.1.1 \( Z \rightarrow \mu\mu \) Inclusive Cross Section Measurement

The measurement of the Z cross section can be performed through a simple di-lepton mass fit, extrapolating the background from sidebands. The main systematics will be due to the evaluation of the following quantities.

**Integrated luminosity** An uncertainties of about 10% is expected from the online luminosity monitor.

**Acceptance** The theoretical systematics due to imperfect MC signal modeling include effects due to PDFs and higher perturbative orders. The main experimental systematics are due to muon momentum scale and resolution.

- **Theoretical uncertainties**
  The differential computation of the perturbative QCD corrections is well established up to the NNLO and the perturbative series show good convergence properties [64]. Also the contribution of the electroweak NLO has been recently addressed [65, 66].
4.1 First Measurements with Muons

Figure 4.1: The CMS trigger efficiency on $Z \rightarrow \mu\mu$ computed with 10 pb$^{-1}$ of data with the tag-and-probe method (red) and with the MC truth (blue). The drops correspond to the crack regions between barrel wheels and in the barrel-endcap transition.

The uncertainty on acceptance due to the remaining higher order corrections and to the factorization has been estimated of the order of 1%, while the impact of the PDF uncertainty should be between 1 and 5% [5, 67].

- **Muon momentum scale and resolution**
  The muon momentum scale can be determined, possibly as a function of the muon kinematic, relying on a likelihood (or $\chi^2$) technique which forces the $Z$ mass to the right nominal value. In Sec. 4.2 the development of such method is described and in Sec. 4.3 the effects on the $Z$ cross section systematics are presented.

Efficiency  The trigger and offline (reconstruction, isolation) lepton efficiencies can be computed from $Z$ data with the *tag-and-probe* method [5, 67].

In Fig. 4.1 the CMS trigger efficiency on a $Z \rightarrow \mu\mu$ sample computed with this technique after 10 pb$^{-1}$ is compared with the efficiency extracted from the MC truth. The difference between the two efficiencies gives the systematic uncertainty of the method ($\sim 0.5\%$). The statistical uncertainty is already negligible ($\sim 0.3\%$) with 50 pb$^{-1}$ and the uncertainty due to the background contribution is less than 0.5%.

Also alternative techniques for the estimation of the efficiency are under study. For instance, the comparison between the numbers of events under the $Z$ peak triggered from one leptons and from two leptons can be exploited [68].
The final cross section measurement should have a systematics smaller than 5% plus the contribution due to the luminosity uncertainty. The statistical error will be negligible very soon thanks to the huge Z production rate at LHC. With higher integrated luminosity also differential measurements will be accessible, like the Z transverse momentum spectrum and the Z cross section as a function of the multiplicity of additional jets.

4.1.2 Heavy Quarkonium production

The production of charmonium and bottomonium states at high-energy colliders has been the subject of considerable interest during the past few years. New experimental results from \( p\bar{p} \), \( ep \) and \( e^+e^- \) colliders have become available, some of which revealed dramatic shortcomings of earlier quarkonium production models. In theory, progress has been made on the factorization between the short distance physics of heavy-quark creation and the long-distance physics of bound state formation. The colour-singlet model \([69, 70]\) has been superseded by a consistent and rigorous framework, based on the use of non-relativistic QCD (NRQCD) \([71]\), an effective field theory that includes the so-called colour-octet mechanisms. Heavy quark pairs that are produced at short distances in a colour-octet state can evolve into a physical quarkonium through radiation of soft gluons at late times in the production process, when the quark pair has already expanded to the quarkonium size. Such a possibility is ignored in the colour-singlet model, where only those heavy quark pairs that are produced in a colour-singlet state and with the spin and angular momentum quantum numbers of the meson are assumed to form a physical quarkonium.

The charmonium production in \( p\bar{p} \) collisions at the Tevatron has attracted considerable attention and has stimulated much of the recent theoretical development in quarkonium physics. The CDF collaboration has measured cross sections for the production of \( J/\psi \) and \( \psi(2S) \) states not coming from \( B \) or radiative \( \chi \) decays, for a wide range of transverse momenta \( 5 \text{ GeV} \leq p_T(\psi) \leq 20 \text{ GeV} \) \([72, 73]\). Surprisingly, the experimental cross sections were found to be orders of magnitudes larger than the theoretical expectation based on the leading-order colour-singlet model \([74, 75]\). This result is particularly striking because the data extend out to large transverse momenta where the theoretical analysis is rather clean.

The CDF results on charmonium production can be explained by including the leading colour-octet contributions and adjusting the unknown non-perturbative parameters to fit the data.

If factorization holds the non-perturbative matrix elements are universal and can be used to make predictions for various processes and observables. Besides a global analysis of different reactions, the measurement of quarkonium cross sections at the LHC will be crucial to assess the importance of the indi-
4.1 First Measurements with Muons

Individual production mechanisms and to test factorization. In Fig. 4.2 the cross section predictions for direct $J/\psi$ and $\psi(2S)$ production as well as the production of $J/\psi$ from radiative $\chi$ decays at the LHC are shown. The theoretical curves include the statistical errors in the extraction of the NRQCD matrix elements from the Tevatron data. There are, however, additional theoretical uncertainties, for instance due to higher-order QCD corrections, which might affect the prediction but which have not yet been fully quantified. The cross

![Graph showing cross sections for $J/\psi$ and $\psi(2S)$ production.](image)

**Figure 4.2:** Cross sections for $J/\psi$ and $\psi(2S)$ production in $pp \rightarrow \psi + X$ at the LHC ($\sqrt{s} = 14$ TeV, $|\eta| < 2.5$). The error bands include the statistical errors in the extraction of the NRQCD matrix elements.

sections collected in Fig. 4.2 should thus not be viewed as firm NRQCD predictions. Another source of potentially large higher-order corrections is the multiple emission of soft or almost collinear gluons from the initial state partons. The effect of initial state radiation can be treated by means of MC event generators which include multiple gluon emission in the parton shower approximation. Comprehensive phenomenological analyses have been carried out for charmonium production at the Tevatron and at the LHC [76, 77, 78] using the event generator PYTHIA [79], supplemented by the leading colour-octet processes [76]. Fig. 4.3 shows the individual contributions to the direct $J/\psi$ cross section at the LHC.
Figure 4.3: Cross sections for $J/\psi$ production in $pp \rightarrow J/\psi + X$ at the LHC ($\sqrt{s} = 14$ TeV, $|\eta| < 2.5$). obtained from PYTHIA event generator [77] and CTEQ2L parton distribution functions [80]. NRQCD matrix elements as specified in [77].

The final prediction is consistent with the result presented in Fig. 4.2 within errors. The extrapolation of the Tevatron fits to LHC energies seems rather insensitive to the details of the underlying theoretical description, since different approaches yield similar predictions for the LHC cross sections as long as the appropriate NRQCD matrix elements are used. The MC implementation should therefore represent a convenient and reliable tool for the experimental simulation of quarkonium production processes at the LHC.

The application of NRQCD should be on safer grounds for the bottomonium system given the larger mass with respect to charmonium. The leading order colour-singlet model predictions underestimate the data, the discrepancy being, however, much less significant than in the case of charmonium. Given the large theoretical uncertainties in the cross section calculation, in particular at small transverse momentum $p_T \leq M_T$, the need for colour-octet contribution is not yet as firmly established as for charmonium production.

Fig. 4.4 shows the inclusive $\Upsilon(1S)$ cross section at the LHC as obtained from the MC calculation.

Finally, the fact that the LHC will produce a large amount of heavy quarkonia with high transverse momentum will also allow for a better discrimination
4.1 First Measurements with Muons

Figure 4.4: Cross sections for $\Upsilon(1S)$ production in $pp \rightarrow \Upsilon(1S) + X$ at the LHC ($\sqrt{s} = 14$ TeV, $|\eta| < 2.5$) obtained from PYTHIA event generator [81] and CTEQ2L parton distribution functions [80]. NRQCD matrix elements as specified in [81].

between different models of heavy quarkonia polarization [82], like NRQCD and the colour-evaporation model. For instance, NRQCD predicts transversely polarized $J/\psi$ and $\psi(2S)$ at high $p_T$. This seems not to be supported by CDF data, although the statistics is too low to draw definitive conclusions.

4.1.2.1 CMS Potential on the $J/\psi \rightarrow \mu\mu$ channel

Various processes contribute to the $J/\psi$ hadro-production: prompt $J/\psi$’s produced directly, prompt $J/\psi$’s from decay of heavier charmonium states such as $\chi_c$, non-prompt $J/\psi$’s from the decay of $B$-hadrons and $J/\psi$’s produced in the parton shower evolution.

An exploratory analysis has been performed on the feasibility of the $J/\psi$ cross section measurement with early CMS data [83]. The measurement is expected not to be limited by statistics but rather by the limited knowledge of the CMS detector, especially at start-up. A dedicated muon trigger path is foreseen which requires two muons with $p_T > 3$ GeV at Level-1 and HLT and with invariant mass between 2.8 and 3.4 GeV at HLT. The expected trigger rates for an instantaneous luminosity of $10^{32}$ cm$^{-2}$ s$^{-1}$ are shown in Table 4.1.
Table 4.1: Combined L1+HLT $J/\psi$ trigger rates at an instantaneous luminosity of $10^{32}$ cm$^{-2}$ s$^{-1}$

<table>
<thead>
<tr>
<th>Trigger rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prompt $J/\psi$</td>
</tr>
<tr>
<td>$J/\psi$ from $B$ decay</td>
</tr>
<tr>
<td>QCD background</td>
</tr>
</tbody>
</table>

The precision tracking permits to disentangle the prompt $J/\psi$’s from those coming from $B$-hadron decays and therefore to determine the fraction of non-prompt $J/\psi$. Fig. 4.5 displays the inclusive $J/\psi$ differential cross section with combined systematic and statistical uncertainties corresponding to an integrated luminosity of 3 pb$^{-1}$. Fig. 4.5 shows also the fraction of $J/\psi$’s from $B$-hadron decays as a function of $J/\psi$ transverse momentum.

![Figure 4.5: Inclusive $J/\psi$ differential cross section, $d\sigma/dp_T \times BR(J/\psi \rightarrow \mu\mu)$ (left) and fraction of $J/\psi$’s from $B$-hadron decays (right) as a function of $p_T^{J/\psi}$, integrated over the pseudorapidity range $|\eta^{J/\psi}| < 2.4$, for an integrated luminosity of 3 pb$^{-1}$.](image)

Already with the small integrated luminosity foreseen to be delivered by the LHC in the first year of operation, it is possible to obtain a result competitive to the Tevatron measurements for $J/\psi$ transverse momenta from about 5 GeV up to about 40 GeV. Afterward, thanks to the much higher collision energy and luminosity with respect to Tevatron, the studies of quarkonia at CMS will probe much higher momentum values. In addition CMS offers a larger pseudorapidity
coverage than that of the Tevatron experiments. Thus it will be possible to extend the test of the different production mechanisms in regions never explored before.

4.2 Muon Calibration

As already stated, muons play a key role in CMS. An optimal resolution on the muon momentum is essential to achieve the goals of the CMS physics program and a precise estimation of this resolution from data is needed to correctly evaluate the systematics in many analyses. For instance, the measurement of the distribution of the $Z$ transverse momentum will be strongly affected by the muon momentum calibration. This measurement has a physics interest related with the computation of the QCD corrections in the soft region of the spectrum. It is also the first step in the estimation of the $Z$+jets cross section, which is an important background for many analyses, like the one presented in Chapter 5. Other obvious examples where the muon calibration is crucial are the Higgs discovery and the Higgs mass measurement in the so called Higgs “golden channel” $H \rightarrow ZZ \rightarrow 4\mu$.

The calibration of the muon momentum scale can rely on well-known di-muon mass resonances ($J/\psi$, $\Upsilon$, $Z$), the main aim being the matching of the reconstructed di-muon mass peak with the resonance nominal mass. One can think to exploit an approach as much simple as possible, taking one of the two muons as reference and calibrating the second one to reconstruct the resonance mass. Unfortunately this would work only if the two muons test uncorrelated regions of the detector, which is not the case, for instance, for muons coming from the $J/\psi$ decay which tend to go in the same direction because the resonance has high boost.

Simple approaches, like the one described, would simply not work for all the events at LHC, a more complex algorithm is necessary which must be able to consider separately the full kinematics of both muons. An iterative algorithm, based on a likelihood approach, for the muon momentum calibration and the measurement of the muon momentum resolution from data has been developed and it is described in Sec. 4.2.1. The results obtained with this algorithm on simulated samples of $J/\psi$, $\Upsilon$ and $Z$ are discussed in Sections 4.2.2 and 4.2.3.

This study is devoted to test the features and the capabilities of the muon calibration algorithm. To this aim the following points are still missing:

- effects of di-muon background,
- excited states of the low mass resonances ($\psi(2S)$, $\Upsilon(2S)$, $\Upsilon(3S)$),
- secondary non-prompt $J/\psi$’s.

However, these issues are not expected to affect the algorithm capabilities under the $Z$ peak. For this reason the analysis is focused mainly on the $Z$ case.
An interesting point, which has still to be addressed, is the computation of
the muon momentum corrections and the measurement of the muon momentum
resolution in the region of very high momenta (> 200 GeV), which is important
for new physics like the search of extra gauge bosons $Z' \rightarrow \mu\mu$. Obviously
no reference resonances are available in this region so the results measured at
low momenta must be extrapolated. This extrapolation is not trivial because
different bias effects can arise at very high $p_T$ regimes ($\sim$ TeV).

4.2.1 Algorithm Description

To first order, the di-muon invariant mass depends linearly on the scale of the
momentum of the muons, so it is possible to determine the momentum scale by
studying the average difference between the reconstructed di-muon mass and
the nominal resonance mass as a function of each muon kinematic variable.
These studies may provide evidence for misalignment and other problems in
the reconstruction. However, if the momentum scale itself is a non-linear func-
tion of those kinematic quantities, its determination by the above method is
biased. In order to avoid relying on averages and to extend single-variable stud-
ies to gain sensitivity to cross-correlations, an unbinned likelihood technique
has been developed which uses ansatz functions for the correction of the muon
momentum:

$$p_T^\prime = F(x_i; a_j) \times p_T$$  \hspace{1cm} (4.1)

and for the estimation of the muon resolution:

$$\sigma_i = G_i(x_i; b_j).$$  \hspace{1cm} (4.2)

The $x_i$ are the muon kinematic variables ($p_T$, $\eta$, $\phi$), $a_j$ and $b_j$ are the parameters
to be computed by the likelihood fit and $\sigma_i$ are the resolutions of each muon
kinematic variable ($\sigma_\eta$, $\sigma_\phi$, $\sigma_{p_T}/p_T$).

The algorithm is based on the minimization of the likelihood

$$L = - \sum_{k=1}^{N_{\text{events}}} \log P(M_k'(F(\mu^+), F(\mu^-), G_i(\mu^+), G_i(\mu^-))),$$  \hspace{1cm} (4.3)

where the probability density function $P$ describing the resonance is the convo-
lution of a Breit-Wigner with a Gaussian, which takes into account the di-muon
mass resolution, plus an ansatz function for the background:

$$P = \int \frac{\Gamma}{2\pi[(M - M_{\text{ref}})^2 + (\Gamma/2)^2]} \times \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(M - M')^2}{2\sigma^2}} dM + B(x_i; c_j).$$  \hspace{1cm} (4.4)

The di-muon mass $M'$ is computed event by event using the corrected transverse
momentum $p_T'$ of eq. 4.1. The reference parameters for the mass ($M_{\text{ref}}$) and
the width ($\Gamma$) in the Breit-Wigner are taken from the fit of the MC generated di-muon mass. The Gaussian mean is set to 0 and the standard deviation $\sigma$ is the resolution of the di-muon mass and it is computed from the ansatz functions for $\sigma_{\eta}$, $\sigma_{\phi}$ and $\sigma_{pT}/p_T$ of eq. 4.2.

The likelihood minimization returns the most likely value of the parameters $a_j$, $b_j$ and $c_j$, which describe the muon momentum corrections, the muon momentum resolution and the di-muon background, given the observed distribution of the reconstructed di-muon mass in the sample.

Inside the algorithm, the fit to the parameters can be repeated iteratively to check its stability. To help in the fit convergence, the parameters can be released one or more at a time in a configurable order.

Meaningful ansatz functions for the momentum correction and the momentum resolution must be chosen. This can be done on the basis of a preliminary study of the mass bias ($M_{\text{ref}} - M(\mu\mu)$) and the muon momentum resolution as a function of each muon kinematic variable, as described in Sections 4.2.2 and 4.2.3. The uncertainty of the fitted parameters, their convergence and stability over various iterations give indications on the correctness of these ansatz functions.

### 4.2.2 Muon Momentum Scale

As a first step, the algorithm is tested on a sample of 11000 $Z \rightarrow \mu\mu$ events, correspondent to 10 pb$^{-1}$ of data, generated with PYTHIA [79]. The resolution is not explicitly parameterized and no background contribution is considered so that the probability density function of the resonance in eq. 4.4 is reduced to a simple Breit-Wigner. The muon momentum scale is computed for each kind of reconstructed muon tracks: global muons (GLB), stand-alone muons (STA) and inner tracker tracks (TRK), which correspond to the various steps of the muon reconstruction described in Sec. 2.3.

The muon momentum scale can be affected by several sources of bias. Two of them are addressed in details: the detector misalignment and the distortion of the magnetic field. The $Z \rightarrow \mu\mu$ sample is reconstructed in several scenarios with different detector performances. The following models of modified reconstruction are considered:

1. 10 pb$^{-1}$ tracker alignment: the detector modules in the simulation are displaced from their original position by a random amount within the uncertainty predicted after an alignment of the tracker performed with the collection of 10 pb$^{-1}$ of data (in [84] a detailed description of this scenario can be found);

2. 10 pb$^{-1}$ muon system alignment: the same procedure described above is applied in the muon chambers, under the hypothesis of a muon system
alignment performed with 10 pb$^{-1}$ of data (wheels and disks have 2 mm uncertainties in $x$ and $y$, 3 mm in $z$ in the barrel and 5 mm in $z$ in the endcap, 250 $\mu$rad uncertainty in rotations, all chambers can move with respect to the wheel/disk by 500 $\mu$m);

3. modified B field intensity: the reconstruction is forced to consider modified intensity of the B field (no change in direction) with the following recipe:

- an upward fluctuation of 0.2% in the solenoid (for $R < 308.755$ cm, $|z| < 661$ cm);
- an upward fluctuation of 2% in the barrel yoke ($R > 308.755$ cm, $|z| < 661$ cm);
- an upward fluctuation of 5% in the endcaps (for $|z| > 661$ cm).

Only muons with $|\eta| < 2.4$ and $p_T > 3$ GeV are considered, the $Z$ boson is reconstructed in each event from the two muons with maximum transverse momentum, if they have opposite charge. Otherwise the $Z$ boson is reconstructed from the two muons with opposite charge and with invariant mass nearest to the nominal $Z$ mass.

As $Z$ reference mass in eq. 4.4, the result from the fit of the peak of the MC generated di-muon mass is considered. In Fig. 4.6 the boson generated mass and the di-muon generated mass are shown. Both are fitted to a Breit-Wigner plus a linear component to describe the $Z/\gamma^*$ interference term. The $Z$ peak is about 50 MeV away from the nominal mass because of the convolution with the PDF, while the di-muon mass peak is further shifted of about 250 MeV because of the QED final state radiation.

The biases on the muon momentum scale have been computed using the following ansatz function, identified by a trial and error procedure:

$$p_T = [a_0 + a_1 p_T + a_2 |\eta| + a_3 \eta^2 + q \times a_4,i sin(\phi + a_5,i)] \times p_T,$$

where $q$ is the muon charge and $i = 1, 2$ stands for $\mu^+$ and $\mu^-$. The biases found on the muon scale for the various kinds of reconstructed muons (TRK, STA, GLB) in the different reconstruction models are listed in Table 4.2. The biases found in the original reconstruction in normal detector conditions is corrected before searching for additional biases due to misalignment and distortion of the magnetic field.

The biases found in global muons and muon tracks are similar (of the order of a few hundred MeV for a 40 GeV muon), accordingly with the fact that the tracker resolution is dominant for muons at the $M(Z)/2$ scale. In the sample used for this analysis the stand-alone muons require, instead, larger corrections. The pattern recognition in the muon spectrometer is, in fact, much more complex than in the tracker. There are many non-gaussian effects which
Figure 4.6: Generated MC Z and di-muon mass. The results of the fits to a Breit-Wigner plus a linear component are reported.
optimization of the stand-alone reconstruction is on-going and better results
finally, in case of showering, the wrong combination of hits can be chosen. The
values compatible with zero (or one) are indicated as zero (or one) or not reported at
all.

<table>
<thead>
<tr>
<th></th>
<th>$a_0$</th>
<th>$a_1$</th>
<th>$a_2$</th>
<th>$a_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLB</td>
<td>$1.006 \pm 0.001$</td>
<td>$(-1.3 \pm 0.3) \times 10^{-4}$</td>
<td>$0$</td>
<td>$(-2.0 \pm 0.9) \times 10^{-3}$</td>
</tr>
<tr>
<td>TRK</td>
<td>$1.005 \pm 0.001$</td>
<td>$(-1.0 \pm 0.2) \times 10^{-4}$</td>
<td>$0$</td>
<td>$(-1.9 \pm 0.9) \times 10^{-3}$</td>
</tr>
<tr>
<td>STA</td>
<td>$1.152 \pm 0.007$</td>
<td>$(-31 \pm 1) \times 10^{-4}$</td>
<td>$(-1.7 \pm 0.8) \times 10^{-2}$</td>
<td>$(6 \pm 4) \times 10^{-3}$</td>
</tr>
</tbody>
</table>

(a) Normal detector conditions

<table>
<thead>
<tr>
<th></th>
<th>$a_0$</th>
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<th>$a_2$</th>
<th>$a_3$</th>
<th>$a_{k+}$</th>
<th>$a_{k-}$</th>
<th>$a_{l+}$</th>
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</thead>
<tbody>
<tr>
<td>GLB</td>
<td>$1.006 \pm 0.002$</td>
<td>$(-1.7 \pm 0.4) \times 10^{-4}$</td>
<td>$0$</td>
<td>$0$</td>
<td>$(5 \pm 1) \times 10^{-4}$</td>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
</tr>
<tr>
<td>TRK</td>
<td>$1.009 \pm 0.002$</td>
<td>$(-9 \pm 3) \times 10^{-4}$</td>
<td>$(6 \pm 2) \times 10^{-4}$</td>
<td>$(5 \pm 0.2)$</td>
<td>$(-3 \pm 2) \times 10^{-4}$</td>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
</tr>
<tr>
<td>STA</td>
<td>$1.024 \pm 0.006$</td>
<td>$(-8 \pm 1) \times 10^{-4}$</td>
<td>$(4.4 \pm 0.8) \times 10^{-4}$</td>
<td>$(6 \pm 4) \times 10^{-4}$</td>
<td>$0$</td>
<td>$0$</td>
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</tr>
</tbody>
</table>

(b) Tracker misalignment (10 pb$^{-1}$)

<table>
<thead>
<tr>
<th></th>
<th>$a_0$</th>
<th>$a_1$</th>
<th>$a_2$</th>
<th>$a_3$</th>
<th>$a_{k+}$</th>
<th>$a_{k-}$</th>
<th>$a_{l+}$</th>
<th>$a_{l-}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLB</td>
<td>$1$</td>
<td>$0$</td>
<td>$0$</td>
<td>$(-2 \pm 1) \times 10^{-4}$</td>
<td>$(1.2 \pm 0.7)$</td>
<td>$(3 \pm 1) \times 10^{-4}$</td>
<td>$(1 \pm 0.5)$</td>
<td>$(1 \pm 0.5)$</td>
</tr>
<tr>
<td>TRK</td>
<td>$1$</td>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
<td>$(2 \pm 1) \times 10^{-4}$</td>
<td>$0$</td>
<td>$0$</td>
</tr>
<tr>
<td>STA</td>
<td>$1.055 \pm 0.007$</td>
<td>$(-1.3 \pm 0.1) \times 10^{-4}$</td>
<td>$0$</td>
<td>$0$</td>
<td>$(1.0 \pm 0.6) \times 10^{-4}$</td>
<td>$(1.5 \pm 0.6)$</td>
<td>$(-1.8 \pm 0.6) \times 10^{-4}$</td>
<td>$(1.4 \pm 0.3)$</td>
</tr>
</tbody>
</table>

(c) Muon system misalignment (10 pb$^{-1}$)

<table>
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<tr>
<th></th>
<th>$a_0$</th>
<th>$a_1$</th>
<th>$a_2$</th>
<th>$a_3$</th>
<th>$a_{k+}$</th>
<th>$a_{k-}$</th>
<th>$a_{l+}$</th>
<th>$a_{l-}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLB</td>
<td>$1$</td>
<td>$(-0.6 \pm 0.3) \times 10^{-4}$</td>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
</tr>
<tr>
<td>TRK</td>
<td>$1$</td>
<td>$(-0.9 \pm 0.5) \times 10^{-4}$</td>
<td>$0$</td>
<td>$0$</td>
<td>$(2 \pm 1) \times 10^{-4}$</td>
<td>$1.4 \pm 0.9$</td>
<td>$(-2 \pm 1) \times 10^{-4}$</td>
<td>$1.4 \pm 0.8$</td>
</tr>
<tr>
<td>STA</td>
<td>$1.039 \pm 0.006$</td>
<td>$(-9 \pm 1) \times 10^{-4}$</td>
<td>$(1.3 \pm 0.8) \times 10^{-4}$</td>
<td>$(7 \pm 4) \times 10^{-4}$</td>
<td>$3.14 \pm 0.001$</td>
<td>$(17 \pm 5) \times 10^{-4}$</td>
<td>$0.3 \pm 0.2$</td>
<td>$(0.3 \pm 0.2) \times 10^{-2}$</td>
</tr>
</tbody>
</table>

(d) B distortion

can induce a scale bias: the multiple scattering and the energy loss in the
material is big, there are regions where the magnetic field is highly not uniform,
finally, in case of showering, the wrong combination of hits can be chosen. The
optimization of the stand-alone reconstruction is on-going and better results
can be obtained with newer samples: presently, a bias of less than 5% can be
found on Z events, i.e., about 1 GeV bias for a muon of 40 GeV.

In Fig. 4.7 the di-muon mass computed in normal detector conditions with
global muons is plotted as a function of the muon pseudorapidity, before and
after the calibration of the muon momentum scale. The parabolic bias versus
$\eta$ is clearly visible and it is completely removed by the calibration procedure.
4.2 Muon Calibration

It should be noted that the parabolic dependence found by the fit of this plot is different from the bias computed with the calibration algorithm (reported in Table 4.2). This is because, in the first case, an average on all the other muon kinematic variables is implicit, while the calibration algorithm computes the dependence of the scale on all the muon kinematic variables at once, taking into account cross-correlations.

In Figures 4.8 to 4.10 the reconstructed mass peak in normal detector conditions, before and after the muon scale calibration, is compared with the MC generated di-muon mass. The peaks are fitted to a Breit-Wigner plus a linear component to describe the $Z/\gamma^*$ interference term. From the fit results it can be appreciated that the calibration procedure is always able to shift the reconstructed mass toward the generated MC value used as input and, to some extent, the peak width is also reduced, suggesting an improvement in the momentum resolution.

The tracker misalignment gives rise to additional biases on tracks as a function of $p_T$ and $\eta$ and to a new sinusoidal dependence on $|\phi|$ of the same order and opposite sign for $\mu^+$ and $\mu^-$ (in eq. 4.5 the charge is factorized). In Fig. 4.11 this sinusoidal scale bias is shown and in Fig. 4.12 the reconstructed mass peak is compared with the one obtained in normal detector conditions. The increase

Figure 4.7: Invariant di-muon mass computed in normal detector conditions with global muons as a function of the muon pseudorapidity, before and after the calibration of the muon momentum scale. Results from parabolic fits are reported.
Figure 4.8: Comparison between the MC generated di-muon mass and the reconstructed mass peak, before and after the muon scale calibration, using stand-alone muons. Results from fits to a Breit-Wigner plus a linear component are reported.
4.2 Muon Calibration

Figure 4.9: Same of Fig. 4.8 for muon tracks.

Figure 4.10: Same of Fig. 4.8 for global muons.
of the peak width is an indication of the big worsening in the resolution due to misalignment.

The tracker misalignment has also sizable effects on the stand-alone reconstruction because it includes a constraint to the vertex position and the precision of the vertex reconstruction is affected by the tracker misalignment.

The muon system misalignment gives rise to additional biases on stand-alone muons as a function of $p_T$ and to a new sinusoidal dependence on $|\phi|$ of the same order and sign for $\mu^+$ and $\mu^-$ (in eq. 4.5 the charge is factorized). Because of the misalignment, the mass peak width increases but part of this resolution worsening is recovered by the calibration procedure, as discussed in Sec. 4.2.3.

In Fig. 4.13 the reconstructed mass peak from muon tracks and stand-alone muons, in case of magnetic field distortion, is compared with the one obtained in normal detector conditions. The 2% increase of the magnetic field in the barrel yoke causes a $p_T$ overestimation of the percent order for stand-alone muons ($a_0 = 1.010 \pm 0.006$); while the 5% increase in the endcaps gives a correction increasing with $|\eta|$ ($a_2, a_3$). Finally the magnetic field distortion causes a sinusoidal dependence on $|\phi|$ for tracks and stand-alone muons of the same order and sign for $\mu^+$ and $\mu^-$ (in eq. 4.5 the charge is factorized and $a_{4,+}$ and $a_{4,-}$ take opposite sign if we consider the periodicity of the phases $a_{5,+}$ and $a_{5,-}$).

The different magnetic field distortion in central and forward regions of the yoke induces a sizable worsening of the resolution of stand-alone muons, which is quite completely recovered by the calibration procedure (details can be found

---

**Figure 4.11:** Invariant di-muon mass computed with muon tracks as a function of the azimuthal angle of $\mu^-$ (left) and $\mu^+$ (right), before and after the calibration of the muon momentum scale. The plots refer to the detector scenario with tracker misaligned. Results from sinusoidal fits are reported.
in Sec. 4.2.3). The injected distortion of the magnetic field inside the solenoid induces instead a pure bias on the muon tracks, which is completely corrected by the calibration procedure, while the induced worsening in resolution is small because the field is increased uniformly in all the tracker region.

4.2.3 Muon Resolution

4.2.3.1 Di-muon Mass Resolution

The di-muon mass resolution can be studied by fitting the reconstructed di-muon mass with a Breit-Wigner (plus an exponential function to describe the $Z/\gamma^*$ interference term) convoluted with a Gaussian:

$$\int \frac{d_0 \Gamma}{2\pi[(M - M_{ref})^2 + (\Gamma/2)^2]} + d_1 e^{-d_2 M} \times \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(M - M')^2}{2\sigma^2}} \, dM,$$

(4.6)

where $d_i$ are free parameters of the fit, $\Gamma$ and $M_{ref}$ in the Breit-Wigner are fixed to the values of the MC generated di-muon mass, the Gaussian mean is set to 0 and the standard deviation $\sigma$ is the di-muon mass resolution to be studied. This analysis was performed on the same sample studied in Sec. 4.2.2 and the results are listed in Table 4.3.
Figure 4.13: Comparison between the MC generated di-muon mass and the mass peak reconstructed with stand-alone muons (above) and muon tracks (below) in normal conditions and with magnetic field distortion, before and after the calibration of the muon momentum scale.
4.2 Muon Calibration

Table 4.3: Di-muon mass resolutions for various kinds of muons in several detector scenarios.

<table>
<thead>
<tr>
<th></th>
<th>GLB</th>
<th>TRK</th>
<th>STA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal conditions</td>
<td>1.06 ± 0.05 GeV</td>
<td>1.03 ± 0.05 GeV</td>
<td>8.5 ± 0.1 GeV</td>
</tr>
<tr>
<td>(a) Normal detector conditions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRK</td>
<td>2.37 ± 0.05 GeV</td>
<td>1.07 ± 0.05 GeV</td>
<td></td>
</tr>
<tr>
<td>STA (before corr.)</td>
<td>10.2 ± 0.1 GeV</td>
<td>9.4 ± 0.1 GeV</td>
<td></td>
</tr>
<tr>
<td>STA (after corr.)</td>
<td>9.7 ± 0.01 GeV</td>
<td>8.7 ± 0.1 GeV</td>
<td></td>
</tr>
<tr>
<td>(b) Modified detector scenarios</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In case of stand-alone muons a sizable improvement in the resolution can be seen after the calibration of the muon momentum scale. The calibration algorithm described in Sec. 4.2.1 is able to correct any smearing effect which is not completely random and which can be described as an analytic function of the muon kinematic variables.

The chosen function for the fit (eq. 4.6) can be further improved. In case of stand-alone muons the convolution with the sum of two Gaussian functions is more suitable. Moreover the final state radiation induces a shoulder effect toward low mass values which can be correctly described, as shown in Fig. 4.14, by a Crystal Ball function:

\[
f(M; \alpha, n, \mu, \sigma) = N \times \begin{cases} 
\exp \left( -\frac{(M-\mu)^2}{2\sigma^2} \right), & \text{for } \frac{M-\mu}{\sigma} > -\alpha \\
A \times (B - \frac{M-\mu}{\sigma})^{-n}, & \text{for } \frac{M-\mu}{\sigma} \leq -\alpha
\end{cases} \quad (4.7)
\]

where

\[
A = \left( \frac{n}{|\alpha|} \right)^n \times \exp \left( -\frac{|\alpha|^2}{2} \right),
\]

\[
B = \frac{n}{|\alpha|} - \alpha.
\]

4.2.3.2 Resolution on Muon Kinematics

If in the calibration algorithm a complete probability density function is considered for the resonance, which also includes the Gaussian convolution as explained in Sec. 4.2.1, it is possible to fit the di-muon mass resolution together
Muon Commissioning with Standard Model Measurements

with the muon scale. This resolution is expressed, inside the likelihood, as a function of the resolution on the muon kinematic variables of eq. 4.4 so that the final results of the likelihood fit are values for the parameters which describe the resolution on these quantities. To this aim, meaningful ansatz functions and starting values of the parameters must be injected as input to the algorithm. So a raw preliminary estimation of the muon resolution as a function of the muon kinematics is needed. This can be computed using a realistic MC description of the detector. The muon resolution is estimated, in this case, using the MC generated values as reference.

The analysis was repeated on three separated samples of 10000 events for each resonance ($J/\psi$, $\Upsilon$, $Z$) and on a single sample with all the three resonances together correspondent to 5.3 pb$^{-1}$ of integrated luminosity. Only the global muons are considered and the samples are reconstructed in a detector scenario with misalignment and miscalibration as expected after a calibration and alignment procedure based on 10 pb$^{-1}$ of data.

For $p_T$ the “relative” resolution is studied, i.e., the difference between reconstructed and generated $p_T$ values divided by the generated one. While for the azimuthal and polar angle the order of magnitude of the resolution is not expected to be directly dependent on the angle itself, thus the “absolute” resolution, i.e., the simple difference between reconstructed and generated values, is considered. The resolution is computed, as a function of the muon kinematics, as the standard deviation of a Gaussian fit in each bin.

For the polar angle the resolution on $\cot \theta$ is considered. In fact, in the barrel region of the tracker, the longitudinal coordinate is measured by the silicon strips while the radial coordinate is fixed by the position of the sensitive modules. The measurement uncertainty is therefore proportional to the

**Figure 4.14:** Fit to the reconstructed Z mass using the convolution with a Gaussian (left) and with a Crystal Ball (right) to describe the resolution.
error on \(\cotg \theta\), the resolution on \(\theta\) or \(\eta\) is instead a non-linear function of the measurement error.

In Figures 4.15 to 4.17 the results of this resolution study are shown. For the 5.3 pb\(^{-1}\) sample, the fits to the resolution shape for the various kinematic variables give:

- \(p_T\) resolution parabolic as a function of \(\eta\) and constant (1.2\%) against \(p_T\)
  \[
  \sigma_{p_T}/p_T = (7.5 + 3.5 \eta) \times 10^{-3} \tag{4.8}
  \]

- \(\phi\) resolution parabolic as a function of \(\eta\) and with \(1/p_T\) dependence
  \[
  \sigma_{\phi} = (3.6 + 0.48 \eta^2) \times 10^{-4} \tag{4.9}
  \]

- \(\phi\) resolution parabolic as a function of \(\eta\) and with \(1/p_T\) dependence
  \[
  \sigma_{\phi} = (0.2 + 2.3/p_T) \times 10^{-3} \tag{4.10}
  \]

- \(\cotg \theta\) resolution parabolic as a function of \(\eta\) and with \(1/p_T\) dependence
  \[
  \sigma_{\cotg \theta} = (5.4 + 4.2 |\eta| + 4.9 \eta^2) \times 10^{-4} \tag{4.11}
  \]
  \[
  \sigma_{\cotg \theta} = (0.39 + 3.2/p_T) \times 10^{-3} \tag{4.12}
  \]

the errors on the parameters are reported in the figures.

Each of these fits relies on an implicit average on all the other kinematic variables. Moreover the resolution of the different variables are considered separately although they are correlated, therefore the same smearing effects can be double-counted in the previous formulas. For instance, the \(1/p_T\) dependence of \(\sigma_{\phi}\) and \(\sigma_{\cotg \theta}\) is already taken into account by \(\sigma_{p_T}/p_T\).

On the other side the muon calibration algorithm, described in Sec. 4.2.1, consider the resolution dependence on the full muon kinematic at once, not implying any average. It also fits the three resolutions \(\sigma_{\cotg \theta}, \sigma_{\phi}, \sigma_{p_T}/p_T\) together, through their impact on the di-muon mass resolution, therefore it takes into account the correlations between them avoiding any double counting. The results of the resolution fit performed with the calibration algorithm are reported in the following.

After a trial and error procedure, the following dependencies were identified:

\[
\sigma_{p_T}/p_T = b_0 + b_1 \eta^2 \tag{4.13}
\]

\[
\sigma_{\phi} = b_2 \tag{4.14}
\]

\[
\sigma_{\cotg \theta} = b_3 \tag{4.15}
\]

Running on the same 5.3 pb\(^{-1}\) sample, the values computed for the parameters are: \(b_0 = (1.36 \pm 0.01) \times 10^{-2}\), \(b_1 = (2.2 \pm 0.1) \times 10^{-3}\), \(b_2 = (1.6 \pm 0.2) \times 10^{-3}\), \(b_3\) compatible with 0.
Figure 4.15: Relative muon $p_T$ resolution ($\sigma_{p_T}/p_T$) as a function of the muon pseudorapidity (above) and the muon transverse momentum (below). The plots on the left refer to three separated samples of 10000 events for each resonance. The plots on the right refer to a single sample with all the three resonances together corresponding to 5.3 pb$^{-1}$ of integrated luminosity.
4.2 Muon Calibration

Figure 4.16: Muon $\phi$ resolution ($\sigma_\phi$) as a function of the muon pseudorapidity (above) and the muon transverse momentum (below). The plots on the left refer to three separated samples of 10000 events for each resonance. The plots on the right refer to a single sample with all the three resonances together correspondent to 5.3 pb$^{-1}$ of integrated luminosity.
Figure 4.17: Muon $\cot\theta$ resolution ($\sigma_{\cot\theta}$) as a function of the muon pseudorapidity (above) and the muon transverse momentum (below). The plots on the left refer to three separated samples of 10000 events for each resonance. The plots on the right refer to a single sample with all the three resonances together correspondent to 5.3 $pb^{-1}$ of integrated luminosity.
4.3 Systematics on Acceptance for the Z Cross Section Measurement

The strategy for the measurement of the inclusive $Z \to \mu\mu$ cross section at LHC and the related systematics are described in Sec. 4.1.1. In particular, the acceptance of muon selection is affected by several sources of uncertainty due to imprecise MC modeling: they can be divided into physics effects (initial and final state radiation, choice of parton distribution functions) and detector description (material budget, efficiency of detector elements and modeling of muon transverse momentum due to our limited knowledge of the physical configuration of the apparatus). In this section we focus in particular on two factors which can strongly affect the measurement of muon momentum and therefore require a careful study: the uncertainty in the position of sensing elements in the detector and the magnitude of the magnetic field. The biases due to these detector effects can be corrected, at least partially, by mean of the calibration algorithm described in Sec. 4.2.1. This procedure may result in a small correction of the measured cross section for $Z$ production: an estimate of the related systematic uncertainty is given in the following.

The systematic uncertainties on the signal cross section measurement, due to the momentum scale calibration and to the imperfect detector behavior (like misalignment and B field distortion), can be evaluated by considering several different scenarios mod $i$ of detector performances and applying the following procedure:

1. perform measurement with a MC simulation of the process, resulting in a reference cross section $\sigma_{\text{orig}}$;

2. apply to muons a scale correction resulting from the calibration procedure, compute new acceptance and new cross section $\sigma_{\text{orig,corr}}$;

3. repeat the MC cross section measurement within modified detector scenarios (with the reconstruction of signal events taking into account the misalignment or B field uncertainties), obtain modified cross sections $\sigma_{\text{mod}_i}$ for several scenarios $i$;

4. apply to muons with modified reconstruction the scale correction resulting from the calibration procedure, compute new acceptance and new cross sections $\sigma_{\text{mod}_i,corr}$.

The systematic uncertainty on the signal cross section due to the muon momentum scale calibration is given by the difference between $\sigma_{\text{orig,corr}}$ and $\sigma_{\text{orig}}$. 
which depends on the effectiveness of our reconstruction under ideal circumstance
\[
syst. = \frac{|\sigma_{\text{orig,corr}} - \sigma_{\text{orig}}|}{100 \times \sigma_{\text{orig}}} \times 100\%.
\]
(4.16)

The systematic uncertainty due to incorrect modeling of alignment and magnetic field map may then be obtained by the difference between the \(\sigma_{\text{mod,corr}}\) value and the \(\sigma_{\text{orig,corr}}\) one, which describe the degradation in performance of the reconstruction (including our correction method) due to imprecise knowledge of the detector:
\[
syst. = \frac{|\sigma_{\text{mod,corr}} - \sigma_{\text{orig,corr}}|}{100 \times \sigma_{\text{orig,corr}}} \times 100\%.
\]
(4.17)

The models of modified reconstruction listed in Sec. 4.2.2 are considered. To compute the cross section systematics the corrections are evaluated on each scenario separately (no corrections from the scenario with normal conditions have been applied pre-emptively).

For the acceptance calculation, the standard cuts defined by the CMS collaboration for the offline selection of \(Z \rightarrow \mu\mu\) events [85] are applied:

- both muons must be in the fiducial region \(|\eta| < 2\);
- both muons must have \(p_T > 20\) GeV;
- the invariant mass of the di-muon pair must be: \(M(\mu\mu) > 40\) GeV (this large mass window allows to study the background from the distribution in the sidebands);
- both muons must be isolated according to the default criteria: \(\sum_{\text{tracks}} p_T < 3\) GeV in a cone \(\Delta R < 0.3\) around the muon.

The systematics are computed from the number of events survived to these cuts. \(Z\) candidates are built from the combination of two global muons (GLB-GLB) or one global muon and one track (GLB-TRK), as second choice, or one global muon and one stand-alone muon (GLB-STA), as third choice. The invariant mass distribution and the background level in the three samples are very different.

The muon momentum corrections are applied after the skimming and before applying the offline selection cuts. This workflow should be equal to the one on real data, except for the fact that we run on the \(Z\) signal only (no background is considered) and we do not apply the HLT selection (however the offline cuts are much stronger than the HLT cuts). The corrections could be applied before the skimming selection, in order to gain some efficiency on the \(Z\) signal, but, with the statistics considered, the skimming efficiency has been found to be comparable, inside the statistical error, in all the scenarios considered with and without corrections.
In Fig. 4.18 the effect of the calibration of muon momentum scale on the \(Z\) boson mass, in case of normal detector behavior, is shown. In Table 4.4 the systematic uncertainty on the \(Z\) boson cross section due to the muon momentum scale correction is reported. It should be noted that this estimation of the systematics is overestimated because the total shift of the acceptance is considered

\[
syst. = \frac{|\sigma_{\text{orig,corr}} - \sigma_{\text{orig}}|}{\sigma_{\text{orig}}} \times 100, \tag{4.18}
\]

while the residual uncertainty on the corrected acceptance, computed after applying the muon scale calibration, is smaller.

![Figure 4.18](image)

**Figure 4.18:** Di-muon mass distribution in \(Z \to \mu\mu\) events selected with the standard cuts listed in the text, before and after applying the calibration of the muon momentum scale. The results of the fits with a Breit-Wigner plus a linear component are reported.

In Table 4.4 the systematics due to the muon momentum scale is reported also if only global muons (GLB-GLB) or only global muons and tracks (GLB-GLB and GLB-TRK) are used to build the \(Z\) candidates. It is evident that the
Table 4.4: Systematic uncertainty on the $Z$ boson cross section due to the muon momentum scale correction. Beside the normal case where global muons, tracks and stand-alone muons are exploited to build the $Z$ candidate, the table includes also the cases where only global muons (GLB-GLB) or only global muons and tracks (GLB-GLB and GLB-TRK) are used.

<table>
<thead>
<tr>
<th>Muon momentum calibration</th>
<th>normal</th>
<th>no stand-alone</th>
<th>only global</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;1.7%</td>
<td>&lt;0.03%</td>
<td>&lt;0.01%</td>
</tr>
</tbody>
</table>

The largest contribution to this systematics comes from the corrections on stand-alone muons. The number of selected $Z \rightarrow \mu\mu$ events increases of about 1.5% (4% after the corrections) by including also the GLB-STA combination for the building of the $Z$ candidates, however also the systematics due to the momentum calibration sizably increases because of the large corrections on the momentum scale of stand-alone muons (see Sec. 4.2.2).

To conclude, in Fig. 4.19 the effects of the misalignment and B field distortion on the $Z$ boson mass, after the muon momentum corrections, are shown. In Tab. 4.5 the corresponding systematic uncertainties on the $Z$ boson cross section are reported. Also the systematics before the muon scale corrections

$$syst. = \frac{\left| \sigma_{\text{mod,}i} - \sigma_{\text{orig,corr}} \right|}{\sigma_{\text{orig,corr}}} \times 100 \%.$$  

are indicated: it can be appreciated that the calibration of the muon momentum scale is able to strongly reduce these systematics.

Table 4.5: Systematic uncertainties on the $Z$ boson cross section due to misalignment and B field distortion. Also the systematics before having applied the muon scale calibration are reported for comparison.

<table>
<thead>
<tr>
<th></th>
<th>before calibration</th>
<th>after calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracker misalignment</td>
<td>3.5%</td>
<td>0.9%</td>
</tr>
<tr>
<td>Muon system misalignment</td>
<td>3.2%</td>
<td>0.3%</td>
</tr>
<tr>
<td>B field distortion</td>
<td>1.8%</td>
<td>0.5%</td>
</tr>
</tbody>
</table>
Figure 4.19: Di-muon mass distribution in $Z \rightarrow \mu\mu$ events selected with the standard cuts listed in the text, after the calibration of the muon momentum scale for the detector modified scenarios described in Sec. 4.2.2. The results of the fits with a Breit-Wigner plus a linear component are reported.
Chapter 5

Standard Model Higgs with high mass: final states with muons

A detailed description of the Higgs discovery strategy at ATLAS and CMS together with an overview of recent theoretical results on the Higgs production and decay can be found elsewhere [86, 87]. Here we will focus on the Higgs decays into final states with muons.

In particular the $H \to VV$ channels, with $V$ being $W$ or $Z$, are discussed. The fully hadronic $VV$ decay cannot be disentangled from the huge QCD background, while the semileptonic final states are overwhelmed by the $V$+jets background. The most promising final states are therefore the fully leptonic ones: 4 leptons for the $ZZ$ case or 2 leptons + 2 neutrinos in case of $WW$, where the leptons can be either muons or electrons.

After a brief review of the Higgs discovery potential in the $H \to ZZ(*) \to 4\ell$ (Sec. 5.1.1) and $H \to WW \to \ell\nu\ell\nu$ (Sec. 5.1.2) channels, the first analysis in CMS of the $H \to ZZ \to \mu\mu\nu\nu$ channel is presented (Sec. 5.2).

5.1 $H \to VV$ Channels

As shown in Fig. 1.6, the favorite Higgs decay in the high mass range ($m_H > 150$ GeV) is $H \to VV$, with $V$ being $W$ or $Z$. The effectiveness of these channels follows very closely the shape of the branching ratio curves. At $m_H \sim 160$ GeV the most promising channel is $WW$, while for heavier Higgs mass the threshold for the on-shell production of the second $Z$ is approached and $ZZ$ becomes the favorite channel for the Higgs discovery. For $m_H > 350$ GeV, the $tt$ channel becomes available and the discovery potential for $VV$ channels is thus reduced. In this very high mass region the $VV$ channels are usually studied in semileptonic final states [88, 89], which have a larger rate with respect to fully leptonic ones.
The theoretical cross sections are known at 3-loop QCD for $H \rightarrow VV$ [90] and 2-loop QCD for $H \rightarrow t\bar{t}$ [91]. The backgrounds to the $H \rightarrow VV$ decay channel are also known at NLO QCD for $WW \rightarrow \ell\nu\ell\nu$, $ZZ \rightarrow 4\ell$ [92] and for $VV$ production via Vector Boson Fusion [93, 94]. Moreover, the $VV$ fusion channel ($VV \rightarrow VV$) is interesting per se, since it is a powerful probe of the electroweak symmetry breaking mechanism. In these processes, either the Higgs is found or unitarity is violated in SM at the TeV scale and new physics must appear. [95, 96].

5.1.1 $H \rightarrow ZZ(\ast) \rightarrow 4\ell$

The $H \rightarrow ZZ(\ast) \rightarrow 4\ell$ process is very interesting over a wide mass range [97], mainly for the very clean signature and the quite high production cross section ($\sigma \sim 5$ - 30 fb for 120 GeV $< m_H < 250$ GeV). The most critical region is 125 - 150 GeV, where one of the $Z$ bosons is off-shell, leading to low-$p_T$ leptons.

The irreducible background $ZZ^*/\gamma^* \rightarrow 4\ell$ has a cross section of the order of 1 pb$^{-1}$ and it is the largest background contribution after the analysis selection. In addition, reducible background comes from $Zb\bar{b}$ and $t\bar{t}$ processes, for which the needed rejection factors of $\sim 10^5$ and $\sim 10^6$, respectively, are achieved using lepton isolation and impact parameter cuts.

The crucial point of the analysis is the lepton identification and reconstruction. Indeed, the main systematic uncertainties are expected to arise from lepton energy scale/resolution and lepton detection efficiency. In order to keep these effects under control, CMS plans to measure them from data exploiting $Z \rightarrow 2\ell$ events.

A sensitivity at 3$\sigma$ level can be obtained for favorable values of Higgs mass ($\sim 200$ GeV) combining $4e$, $4\mu$ and $2e2\mu$ final states with only 1 fb$^{-1}$ of integrated luminosity.

5.1.2 $H \rightarrow WW \rightarrow l\nu l\nu$

This fully leptonic final state ($\sigma \sim 0.5$-2.5 fb for 120 GeV $< m_H < 200$ GeV) is particularly clean but it has the big drawback of not allowing the Higgs mass peak reconstruction. An alternative variable to discriminate signal and backgrounds is the azimuthal opening angle between the two charged leptons ($\Delta \phi(l\ell)$). In the SM the Higgs boson has 0 spin so the lepton (left-handed) and the anti-lepton (right-handed) tends to go in the same direction and $\Delta \phi(l\ell)$ is small. This is a good assumption only for not too high Higgs mass (under 200-250 GeV), otherwise the high boost of the $W$ bosons pushes the two charged leptons into opposite directions.

The reconstruction and selection of the $H \rightarrow WW \rightarrow l\nu l\nu$ signal exploits the full detector functionality: muon and electron detection, transverse missing
energy ($E_T$) measurement, central jet veto. Therefore careful strategies to measure the interesting detector performances from data are needed: the lepton detection efficiency can be extrapolated from the efficiency computed on single-Z sample exploiting the tag-and-probe technique; to evaluate the impact of the $W$+jets background, the lepton fake rate must be measured from QCD multi-jets events; finally, the systematics on the missing energy can be estimated from the $W$ mass measurement or by building an $E_T$ template from $Z$ data (with one lepton artificially removed).

Because of lack of mass peak, a careful strategy for background normalization from data is needed. The rate of the main backgrounds ($t\bar{t}$ with $\sigma \sim 86$ pb, $WW$ with $\sigma \sim 12$ pb, in fully leptonic final states) in the signal region is extrapolated from dedicated control regions, where the signal rate is negligible, using a rescaling factor evaluated from MC. A detailed study of the impact of theoretical uncertainties (mainly due to the $gg \rightarrow WW$ MC description and double top with single top interference) has been carried out in the ATLAS collaboration [98], showing an uncertainty of about 5% and 10%, respectively, on $WW$ and $t\bar{t}$ rate in the signal region. Given these systematics, a Higgs discovery at $m_H \sim 160$ GeV would require less than 2 fb$^{-1}$. A CMS study [99] also takes into account the experimental systematics due to luminosity, lepton identification efficiency, misalignment and miscalibration, $E_T$ resolution, jet energy scale and jet reconstruction efficiency. It shows that an integrated luminosity of 1 fb$^{-1}$ should be enough to discover a Higgs boson of 160 GeV, combining the three final states $2e$, $2\mu$ and $e\mu$.

5.2 A New Channel: $H \rightarrow ZZ \rightarrow \mu\mu\nu\nu$

This signal has the same final state of the $H \rightarrow WW \rightarrow \mu\nu\mu\nu$ channel but it has never been studied in details in CMS, while ATLAS performed a dedicated analysis in the past [100]. The amount of background in this channel is expected to be higher with respect to the $H \rightarrow WW \rightarrow \mu\nu\mu\nu$ case, where the large $Z/\gamma^* \rightarrow \mu\mu$ contribution can be rejected requiring a di-muon mass far away from the nominal $Z$ mass. However, as already said in Sec. 5.1.2, for very high Higgs mass ($> 200$ GeV) the discriminant power of the $H \rightarrow WW$ analysis strongly decreases because the $W$ boost affects the azimuthal opening angle between the two charged leptons, which is used to define the signal region. Moreover recent D0 results [101] have shown that the study of the $ZZ \rightarrow \mu\mu\nu\nu$ process can really be promising, relying on a cut on $E_T$ to reject the $Z/\gamma^* \rightarrow \mu\mu$ contribution.

As discussed in Sec. 5.1.1, the other fully leptonic channel candidate for the Higgs discovery at high mass is $H \rightarrow ZZ \rightarrow 4\ell$. As shown in Fig. 5.1, the $H \rightarrow ZZ \rightarrow \mu\mu\nu\nu$ channel has the advantage of a branching ratio about
ten times larger with respect to the $H \rightarrow ZZ \rightarrow \mu\mu\mu\mu$ channel. This fact can make the $H \rightarrow ZZ \rightarrow \mu\mu\nu\nu$ channel particularly interesting for very high Higgs mass, for which the Higgs production rate is very low because of the exponential decrease of the Higgs production cross section shown in Fig. 1.5.

![Figure 5.1: Number of events in $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$ channel and in $H \rightarrow ZZ \rightarrow 4\ell$ channel as a function of the Higgs mass ($\ell$ can be $\mu$ or $e$). The NLO Higgs production cross section and NLO Higgs BR are used [102]. Only the poissonian statistical errors are reported.](image)

The $H \rightarrow ZZ \rightarrow \mu\mu\nu\nu$ analysis presented in the following is the first ever performed in CMS. It has to be intended as a preliminary study to explore the feasibility of the Higgs detection in this final state. The results here presented cannot be conclusive for many reasons:

- the low MC statistics of the background samples,
- the lack of the NLO reweighting of the Higgs transverse momentum distribution,
- the uncertainties in the MC description of the transverse momentum distribution of the $Z/\gamma^* \rightarrow \mu\mu$ background (a careful measurement from data at the LHC energy would be needed),
- the lack of pile-up simulation.
The aims of this analysis are the exploration of the signal features, the estimate of the relative importance of the various backgrounds, the definition of a sensible strategy to discriminate between them and a preliminary discussion of the impact of the main systematic uncertainties.

### 5.2.1 Signal Kinematic

The signal simulation is performed with PYTHIA [79]. This is a LO MC which accounts for the two main contributions to the Higgs production: gluon-gluon fusion (ggf) and Vector Boson Fusion (VBF). Two Higgs mass values are considered in this study: 200 GeV and 500 GeV. The corresponding cross sections at NLO [102] and the generated integrated luminosities are listed in Table 5.1. The plots in this Section, in Sec. 5.2.2 and in Sec. 5.2.3 refer to the $m_H = 200$ GeV case; increasing the Higgs mass, the difference between the signal kinematic and the background one is enhanced, as shown in Sec. 5.2.4.2.

<table>
<thead>
<tr>
<th>$m_H$</th>
<th>$\sigma_{NLO}$</th>
<th>Integrated $\mathcal{L}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$200$ GeV</td>
<td>61.2 fb</td>
<td>461 fb$^{-1}$</td>
</tr>
<tr>
<td>$500$ GeV</td>
<td>15.58 fb</td>
<td>822 fb$^{-1}$</td>
</tr>
</tbody>
</table>

It should be noted that the relative weight of the ggf and the VBF contributions given by PYTHIA is computed at LO (73% and 27%, respectively, for $m_H = 200$ GeV), while the NLO computation gives different values (85% and 15%, respectively, for $m_H = 200$ GeV). This has an impact on the Higgs transverse momentum distribution which should be therefore reweighted to match the NLO computation to have a more correct description of the signal kinematic.

In Figures 5.2 and 5.3 the signal kinematic at generation level is shown (the muon kinematic is considered before the final state radiation).

The Higgs transverse momentum distribution is peaked at very low values ($\sim 10$ GeV) but at leading order there is a long queue at high values which is mainly due to VBF. The $Z$ transverse momentum is peaked at quite low values ($\sim 35$ GeV) like the muon transverse momentum ($p_T^\mu \sim M_Z/2$).

The Higgs boson is strongly boosted in the longitudinal direction, the $Z$ bosons have therefore high pseudorapidity and little pseudorapidity distance. The leptons are instead more central and they have moderate pseudorapidity distance.
5.2.2 Resolution and Efficiency

5.2.2.1 Missing Transverse Energy ($E_T$) Corrections

The $E_T$ is computed starting from all the energy deposits in the calorimetric towers beyond a given threshold [103]. The $E_T$ calculation can be improved applying the Jet Energy Scale (JES) corrections: they are essential to remove biases due to the non-linear response of the calorimeters to jet energy deposits at different values of transverse energy and pseudorapidity. Standard MC-based jet corrections are applied. The relative response of the calorimeters is defined as the ratio of the transverse energy of the reconstructed and MC-generated jet.
The MC corrections are derived by fitting the relative response with a Gaussian in each bin of transverse energy and pseudorapidity. This technique takes into account non-uniformity and non-linearity of the calorimeters [104].

Moreover in most of the cases the muons deposit only very little energy in the calorimeters. Hence in the $E_T$ computation the energy measured along the muon trajectory in the calorimeters is replaced by the actual muon momentum measured by the inner tracker and the muon system together.

In Fig. 5.4 (left) the reconstructed $E_T$ distribution, with and without corrections, is compared with the generated $E_T$. The latter accounts for all the generated stable particles except muons and neutrinos, it has been therefore corrected to take into accounts also muons. The corrected generated $E_T$ matches very well the transverse momentum distribution of the signal $Z \rightarrow \nu \nu$.

In Fig. 5.4 (right) the $E_T$ resolution after the corrections is shown. The resolution is mainly Gaussian ($\sigma \sim 33\%$) with a mean underestimated of 10\% and a non-Gaussian queue toward overestimated values of reconstructed $E_T$.

![Figure 5.4: Comparison between generated and reconstructed $E_T$ (left). $E_T$ resolution with all corrections applied, a Gaussian fit is superimposed (right).](image)

### 5.2.2.2 Muon Resolution and Efficiency

The muons are reconstructed combining the inner tracker and the muon system information: the so called global muons, defined in Sec. 2.3.2, are used. The resolution of the muon and the $Z \rightarrow \mu \mu$ momenta are listed in Table 5.2. The core of the resolution distributions have a clean Gaussian shape, as shown in Fig. 5.5.

To estimate the muon acceptance and the muon reconstruction efficiency a reconstructed global muon with $\Delta R < 0.1$ with respect to the generated muon is
Table 5.2: Resolutions on the muon momentum and the \( Z \rightarrow \mu\mu \) momentum and mass. The resolution distributions are fitted to Gaussian functions and the corresponding standard deviations are listed. The fit uncertainties on these resolutions are of the order of \( 10^{-4} \)

<table>
<thead>
<tr>
<th></th>
<th>resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>muon ( p_T )</td>
<td>1.6%</td>
</tr>
<tr>
<td>muon ( p_z )</td>
<td>1.6%</td>
</tr>
<tr>
<td>muon ( E )</td>
<td>1.6%</td>
</tr>
<tr>
<td>( Z ) ( p_T )</td>
<td>1.9%</td>
</tr>
<tr>
<td>( Z ) ( p_z )</td>
<td>1.9%</td>
</tr>
<tr>
<td>( Z ) ( E )</td>
<td>1.5%</td>
</tr>
<tr>
<td>( Z ) mass</td>
<td>1.3%</td>
</tr>
</tbody>
</table>

Figure 5.5: Resolution of the muon transverse momentum (left) and of the \( Z \rightarrow \mu\mu \) mass (center) and transverse momentum (right), with Gaussian fits superimposed. The results of the fits are listed in Table 5.2

required. In Fig. 5.6 the transverse momentum and pseudorapidity distributions of the lost muons are shown. The overall acceptance is \((86.0 \pm 0.1)\%\) while the reconstruction efficiency in the fiducial region \( \eta < 2.4 \) is \((98.16 \pm 0.06)\%\). As can be seen in Fig. 5.7, the lost in efficiency is mainly due to muons with low transverse momentum \((p_T < 5 \text{ GeV})\) or crossing the crack regions. In particular the large efficiency lost at \( \eta \sim 0.25 \) is due to the transition region from wheel 0 to wheels +/-1.

5.2.3 Main Backgrounds

The \( H \rightarrow ZZ \rightarrow \mu\mu\nu\nu \) channel suffers from a large amount of background. The kinematic of the most important background processes is compared with the signal one in Fig. 5.8. The corresponding cross sections are listed in Table 5.3,
5.2 A New Channel: $H \to ZZ \to \mu\mu\nu$

![Graphs and plots]

**Figure 5.6:** Pseudorapidity and transverse momentum distributions of the generated muons without any reconstructed global muon with $\Delta R < 0.1$. In the first two plots (left and center) the overall distributions of all the generated muons is shown for comparison, in the last plot only the lost muons are considered (right).

![Graphs and plots]

**Figure 5.7:** Muon acceptance (black) and reconstruction efficiency (red) as a function of the transverse momentum (left). Convolution of muon acceptance and reconstruction efficiency as a function of the pseudorapidity (right).

... together with the generated integrated luminosity and the MC generators used for the simulation.

The most problematic background is due to single-$Z$ production. Beside the high cross section, this process has also a kinematic quite similar to the signal: the largest differences are the lower $Z$ transverse momentum, the bigger $Z$ pseudorapidity and the absence of neutrinos in the final state, so that the $E_T$ in this background is only due to detector acceptance and calorimeter reso-
Table 5.3: List of the main background processes: the MC generators, the cross sections and the generated integrated luminosity are reported. In the $W+\text{jets}$ sample $200 \text{ pb}^{-1}$ are generated for $W+0 \text{ jets}$ and $1 \text{ fb}^{-1}$ for $W+n \text{ jets}$ with $n>0$. Up to 5 jets are considered in $Z+\text{jets}$ and $W+\text{jets}$ samples. Up to 4 jets in the $t\bar{t}+\text{jets}$ sample. In all the cases PYTHIA is used for the parton shower evolution and the hadronization. In all the AlpGen samples the so called “MLM” procedure [105] is applied to match the matrix element computation of the hard scattering and the parton shower evolution.

<table>
<thead>
<tr>
<th>Process</th>
<th>Generator</th>
<th>Cross Section</th>
<th>Integrated Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \mu\mu$</td>
<td>PYTHIA</td>
<td>829 pb</td>
<td>1.18 fb$^{-1}$</td>
</tr>
<tr>
<td>$Z+\text{jets}$</td>
<td>AlpGen</td>
<td>5777 pb</td>
<td>1 fb$^{-1}$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>MC@NLO</td>
<td>840 pb</td>
<td>1.21 fb$^{-1}$</td>
</tr>
<tr>
<td>$t\bar{t}+\text{jets}$</td>
<td>AlpGen</td>
<td>837 pb</td>
<td>2 fb$^{-1}$</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>PYTHIA</td>
<td>15.3 pb</td>
<td>9.2 fb$^{-1}$</td>
</tr>
<tr>
<td>$WW$</td>
<td>PYTHIA</td>
<td>114.3 pb</td>
<td>7.4 fb$^{-1}$</td>
</tr>
<tr>
<td>$W+\text{jets}$</td>
<td>AlpGen</td>
<td>5777 pb</td>
<td>200 pb$^{-1}$/1 fb$^{-1}$</td>
</tr>
</tbody>
</table>

A sample of single-$Z$ generated with PYTHIA and a sample produced with AlpGen [106] are considered. The latter contains the matrix element computation of the LO $Z+\text{jets}$ contribution up to 5 jets and the so called “MLM” procedure [105] is applied to match the hard scattering part, computed by the matrix element MC, with the parton shower evolution done by PYTHIA. As explained in the following (Sec. 5.2.4.2), the analysis strategy strongly relies on cuts based on the $Z$ transverse momentum, on the $E_T$ distribution and on isolation variables. All these features are highly affected in case of additional hard jets which can recoil with respect the $Z$ and they cannot be studied in the PYTHIA sample.

Another background process with large cross section is $t\bar{t}$, which however has a kinematic quite different from the signal. The muons come from a $W$ decay or from the fragmentation of a $b$ quark, therefore they have lower transverse momentum with respect to the signal and their invariant mass is not peaked at the $Z$ mass. Two different MC samples are considered for this process: one sample generated with MC@NLO [107, 108], plus Herwig [109] for the parton shower, the other sample is generated with AlpGen, plus PYTHIA for the parton shower. While MC@NLO includes all the NLO virtual and real corrections, the AlpGen sample contains the LO $t\bar{t}+\text{jets}$ contribution up to 4 jets.

The irreducible $Z/\gamma^*Z/\gamma^*$ background is generated with PYTHIA. The difference with respect to the signal kinematic is very little: slightly bigger muon transverse momentum and pseudorapidity. The difference in the $E_T$ distribu-
tion of Fig. 5.8 is due to the fact that the $Z/\gamma^* Z/\gamma^*$ sample is inclusive (i.e., all the $Z$ decay channels are open) therefore only a subset of the events has two neutrinos in the final state. It should be noted that the PYTHIA generation misses the NNLO $gg \rightarrow ZZ$ contribution which amounts to $(20 \pm 8)\%$ of the LO cross section [110].

The $WW$ background has the same final state of the signal. An inclusive sample generated with PYTHIA is considered. The main difference with respect to the signal is the absence of the $Z \rightarrow \mu\mu$ mass peak.

Finally, also a sample of $W+$jets events, up to 5 jets, was generated with AlpGen, exploiting PYTHIA for the parton shower. This sample, as well as the other AlpGen samples, are not shown in Fig. 5.8 because they are used only at the second stage of the analysis to optimize the final selection cuts (Sec. 5.2.4.2).

Figure 5.8: Comparison between signal and background kinematic: muon transverse momentum (above, left) and pseudorapidity (above, center), $Z$ transverse momentum (above, right), pseudorapidity (below, left) and mass (below, center), $E_T$ (below, right). All the plots have the same arbitrary normalization and they refer to reconstructed variables after the trigger and skimming selections described in Sec. 5.2.4.1.
5.2.4 Analysis Strategy

5.2.4.1 Trigger, Skimming and Preselection

The trigger requires at least one muon with high transverse momentum. The used trigger paths are listed in Table 2.2.

A preliminary skimming procedure is foreseen in CMS in order to define the data stream. The same skimmed samples of the $H \rightarrow WW$ channel are used: two global muons with $p_T > 10, 20$ GeV and $|\eta| < 2.4$ are required by the skimming.

The standard CMS analysis flow includes then a preselection step with the aim of cutting as much as possible the amount of data to be further analyzed, without losing too much signal efficiency. Many simple variables were studied in order to cut at the preselection level: beside the kinematic ones, also cuts related with the muon isolation, impact parameter and track quality were considered. At the end the following preselection cuts are chosen:

- exactly two muons with opposite charge,
- $80$ GeV $< M(\mu\mu) < 100$ GeV,
- $E_T > 25$ GeV.

As shown in Fig. 5.9 (left), the number of muons per event is two in 97% of the signal events while in $tt$ and $ZZ$ backgrounds there are more than two muons in 26% and 10% of events, respectively. In the $tt$ process the muons can come not only from the $W$ decay but also from the $b$ quark fragmentation, moreover in the dense hadronic activity, proper to this kind of events, there can be more decays in flight of $\pi$’s and $K$’s into muons with respect to electroweak processes. In the $ZZ$ process also the second $Z$ boson can decay into muons.

The probability of charge misidentification is practically negligible for global muons with $p_T < 200$ GeV. Therefore in the signal events with wrong muon charge combination (0.15% considering only events with exactly two muons), one of the signal muons from the $Z$ decay escapes undetected while a muon produced from the fragmentation of a $b$ or $c$ quark or from the decay of some $\pi$ or $K$ particle is chosen as signal muon. This kind of events would give a wrong reconstructed Higgs kinematic, so they must be rejected. Moreover, as shown in Fig. 5.9 (right), it can happen quite frequently that the two muons in the backgrounds have the wrong charge combination (24.8% in the $tt$ process and 3.3% in the $WW$ process, considering only events with exactly two muons). This is because the muons in these backgrounds do not come from a $Z$ decay. This kind of backgrounds can be also easily rejected requiring a di-muon invariant mass similar to the nominal $Z$ mass (as already shown in Fig. 5.8).

All the mentioned preselection cuts have very little impact on the single-$Z$ background. In order to reject it, a cut must be applied on the $E_T$ (as already
Figure 5.9: Number of muons per events (left) and muon charge combination only for event with exactly two muons (right): -1 means $\mu^+\mu^-$ combination, +1 indicates two muons with same charge. All the processes have the same arbitrary normalization.

shown in Fig. 5.8), which is also powerful against the ZZ background for events where no one of the two $Z$’s decays into neutrinos.

In Fig. 5.10 the efficiencies of the preselection cuts for the various processes are shown. In Table 5.4 the efficiencies after HLT, skimming and preselection are listed and in Fig. 5.11 the corresponding numbers of events for 1 fb$^{-1}$ are reported. In Fig. 5.11 also the AlpGen samples ($Z$+jets, $t\bar{t}$+jets and $W$+jets) are reported for comparison.

In the $Z$+jets sample the $Z$ is free to decay in any lepton family. A generation cut ($M(\mu\mu) > 40$ GeV) is applied in the $Z \rightarrow \mu\mu$ PYTHIA sample. For these reasons the generated cross sections of the two samples are so much different; however, after the preselection, the number of predicted events is similar, the difference being due to the different kinematic in the two MC generators.

In the $t\bar{t}$ case, the two samples have quite similar cross sections because they have been generated with no cuts and MC@NLO includes also the real NLO corrections to the $t\bar{t}$ process, i.e. $t\bar{t}+1$ jets. However the number of expected events after the preselection is different in the two samples indicating a sizable difference in the generated kinematic. For the optimization of the selection strategy (Sec. 5.2.4.2) the AlpGen samples are considered.

As reported in Table 5.4, after the HLT, the skimming and the preselection the sum of all the backgrounds is reduced to about 5% of the generated cross section while about 50% of the signal is lost (30% for a Higgs mass of 500 GeV). In Fig. 5.12 the signal efficiency of each selection step is shown as a function of
Figure 5.10: Efficiency of each preselection cut for signal and background processes. The efficiency of the requirement of the right muon charge combination is computed only for events with exactly two muons.

the muon transverse momentum and pseudorapidity. The efficiency is computed as the ratio of the number of selected events over the number of generated events, therefore the acceptance is included. No unexpected biases are induced on the muon kinematic distributions by the applied selections.

5.2.4.2 Signal Selection

With 1 fb\(^{-1}\) of integrated luminosity, after the preselection cuts, of the order of 60000 background events and about 30 (10) signal events are expected for a Higgs mass of 200 (500) GeV. The dominant background is \(Z+\text{jets}\) which amounts to about 97% of the total background.

In Fig. 5.13 the distributions of the main kinematic variables are shown for signal and backgrounds after the preselection cuts. The signal behavior in case of high Higgs mass is very different from the background. The sample with smaller Higgs mass has, instead, a kinematic similar to the \(Z+\text{jets}\) sample: the largest differences being the bigger \(E_T\) and the smaller \(Z\) transverse momentum.

The intentional choice of not applying Higgs mass dependent cuts has been taken. This kind of analysis would need a large amount of MC data samples in order to perform a reliable optimization as a function of the Higgs mass. This analysis optimization is considered premature with the available MC samples.
5.2 A New Channel: $H \rightarrow ZZ \rightarrow \mu\mu\nu\nu$

Figure 5.11: Number of events after 1 fb$^{-1}$ of integrated luminosity at each step of the preliminary selection (HLT, skimming and preselection) for signal and background processes. For the AlpGen samples ($Z$+jets, $t\bar{t}$+jets and $W$+jets) only the generated cross sections and the final yields after the preselection are reported for comparison with the other background samples.

Figure 5.12: Signal efficiency at the various selection steps (HLT, skimming and preselection) as a function of the muon pseudorapidity (left) and transverse momentum (right) for a Higgs mass of 200 GeV. The acceptance is included.
Table 5.4: Compound efficiencies of HLT, skimming and preselection on signal and background processes. The statistical uncertainties are reported.

<table>
<thead>
<tr>
<th></th>
<th>HLT</th>
<th>skimming</th>
<th>preselection</th>
</tr>
</thead>
<tbody>
<tr>
<td>signal MH200</td>
<td>(91.5 ± 0.2)%</td>
<td>(71.5 ± 0.3)%</td>
<td>(49.7 ± 0.3)%</td>
</tr>
<tr>
<td>signal MH500</td>
<td>(93.4 ± 0.2)%</td>
<td>(83.1 ± 0.3)%</td>
<td>(68.2 ± 0.4)%</td>
</tr>
<tr>
<td>Z → μμ</td>
<td>(95.60 ± 0.02)%</td>
<td>(83.62 ± 0.04)%</td>
<td>(9.54 ± 0.03)%</td>
</tr>
<tr>
<td>tt</td>
<td>(17.36 ± 0.03)%</td>
<td>(3.87 ± 0.02)%</td>
<td>(0.203 ± 0.004)%</td>
</tr>
<tr>
<td>ZZ</td>
<td>(8.17 ± 0.08)%</td>
<td>(4.58 ± 0.06)%</td>
<td>(1.40 ± 0.03)%</td>
</tr>
<tr>
<td>WW</td>
<td>(12.79 ± 0.03)%</td>
<td>(0.79 ± 0.01)%</td>
<td>(0.071 ± 0.003)%</td>
</tr>
</tbody>
</table>

It should be also noted that simple cuts to select the high Higgs mass signal, which can be suggested by Fig. 5.13 (like cuts on the Z transverse momentum, the $E_T$ or the azimuthal angle between the two muons) would not help so much in rejecting background in the interesting kinematic region of high Higgs transverse mass (which will be discussed in Sec. 5.2.5).

A variable has been identified which has similar behavior for different Higgs masses and which is effective in rejecting the $Z+$jets background: $p_T(\mu \mu)/E_T$. In the signal this corresponds to the ratio of the transverse momenta of the two $Z$ bosons: they should be equal for all the Higgs masses, the Higgs transverse momentum being relatively small. Actually from Fig. 5.14 the $E_T$ seems to be overestimated in the smaller Higgs mass case, this is probably due to not optimal corrections of the calorimeter non-linearity, as can be suggested by the biased $E_T$ resolution (Fig. 5.4). The $E_T$ bias can depend on the underlying event activity which increases with the energy scale of the correlated hard scattering process, i.e., with the Higgs mass in the signal. As already discussed, the $Z+$jets background has not physical $E_T$ and quite sizable $Z$ transverse momentum, the $Z$ recoiling with respect to the additional jets and the underlying event.

The signal selection can also rely on a central jet veto and isolation cuts, taking advantage of the presence of additional jets in the background events. In Fig. 5.15 the background efficiency against the signal efficiency is reported for various possible configurations of track counting veto: a maximum number of tracks is allowed in a given pseudorapidity range, considering only tracks with transverse momentum above a certain threshold. No sizable gain in significance is reachable with this kind of cut. An analogous study based on calorimetric jets gave similar results. The efficiency lost in the signal is mainly due to the two additional jets in VBF events. They tend to go in the forward-backward regions of the detector, however in events with high longitudinal boost one of the two jets can be in the central region. Part of the efficiency lost is also due to the hadronic activity in the underlying event, recoiling with respect to the
5.2 A New Channel: $H \to ZZ \to \mu\mu\nu

Higgs. As can be seen in Fig. 5.15 the track counting veto efficiency is lower on the signal sample with higher Higgs mass and therefore higher underlying event activity.

Better results can be obtained studying the muon isolation. The sum of transverse momenta of tracks (or the sum of transverse energies of calorimetric deposits) inside a cone of fixed size ($\Delta R = 0.3$) around the muon is computed. Various isolation variables are built combining tracker and calorimetric information with different relative weights. The isolation of each single muon can be separately considered or, alternatively, the sum of the isolation variables of the two muons can be studied. In this analysis the best results are obtained with the isolation variable defined as

$$2 \times \sum_{\text{tracks}} p_T + 1.5 \times \sum_{\text{ECAL}} E_T + \sum_{\text{HCAL}} E_T$$

(5.1)

and considering only the muon with smaller transverse momentum between the two muons selected at preselection level. The distribution of this isolation variable and the efficiency of a possible cut on it are shown in Fig. 5.16. A strong rejection is achieved against the $W+$jets background, where the second muon is always produced by the decay of a hadron inside a jet. Also the $t\bar{t}+$jets rejection is high because the events where the second muon does not come from a $W$ decay but it’s produced inside a jet can be rejected. Moreover the hadronic activity in a QCD process, like $t\bar{t}+$jets, is usually high and therefore also the muons coming from a $W$ decay tend to be less isolated with respect to electroweak initiated processes. For what concerns the signal, contrary to the central jet veto, the two jets produced in VBF events have negligible impact on the muon isolation: the pseudorapidity difference is, in fact, a Lorentz invariant quantity, therefore the distance of the jets with respect to the muon is always quite large, also for events with high longitudinal boost. Finally the underlying event activity also have small influence on the muon isolation because the underlying event recoils with respect to the Higgs, being therefore in the hemisphere opposite to the muons.

A typical variable which is also exploited in the analysis of the $H \to VV$ channels is the muon impact parameter (IP). Actually the significance of the muon transverse IP (i.e., $d_0/\sigma(d_0)$) should be considered to take correctly into account the uncertainty on the IP measurement. Also in this case only the muon with smaller transverse momentum, between the two selected at preselection level, is considered. As can be seen in Fig. 5.17, this variable is powerful in rejecting $W+$jets and $t\bar{t}+$jets where the second muon can come from the fragmentation of a $b$ quark or from a $K$ or $\pi$ decay inside a jet. Given the $M(\mu\nu)$ cut at preselection level, also in the $WW$ inclusive process the pollution of muons coming from a jet is expected to be higher with respect to process
with a real $Z \to \mu\mu$ decay. On the other hand the efficiency on the dominant $Z$+jets background is very high making this cut useless to increase the signal significance.

In Table 5.5 the best selection cuts are listed with the corresponding efficiency.

Table 5.5: Preselection and detailed selection efficiencies for signal and background processes. The selection efficiencies are computed considering only survival events after preselection step.

<table>
<thead>
<tr>
<th></th>
<th>MH200</th>
<th>MH500</th>
<th>ZZ</th>
<th>WW</th>
</tr>
</thead>
<tbody>
<tr>
<td>preselection</td>
<td>(49.7±0.3)%</td>
<td>(68.2±0.4)%</td>
<td>(1.40±0.03)%</td>
<td>(7.1±0.3)×10⁻⁴</td>
</tr>
<tr>
<td>$p_T(\mu\mu)/\slashed{E}_T &lt; 1.6$ isolation&lt;2 GeV</td>
<td>(84.1±0.3)%</td>
<td>(91.0±0.3)%</td>
<td>(54±1)%</td>
<td>(90±1)%</td>
</tr>
<tr>
<td>selection</td>
<td>(73.7±0.4)%</td>
<td>(79.2±0.4)%</td>
<td>(41±1)%</td>
<td>(67±1)%</td>
</tr>
<tr>
<td>all cuts</td>
<td>(36.6±0.3)%</td>
<td>(54.0±0.4)%</td>
<td>(0.63±0.02)%</td>
<td>(4.8±0.2)×10⁻⁴</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Z+jets</th>
<th>t\bar{t}+jets</th>
<th>W+jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>preselection</td>
<td>(1.042±0.004)%</td>
<td>(8.1±0.3)×10⁻⁴</td>
<td>(1.15±0.04)×10⁻⁵</td>
</tr>
<tr>
<td>$p_T(\mu\mu)/\slashed{E}_T &lt; 1.6$ isolation&lt;2 GeV</td>
<td>(52.9±0.2)%</td>
<td>(74±2)%</td>
<td>(66±2)%</td>
</tr>
<tr>
<td>selection</td>
<td>(38.2±0.2)%</td>
<td>(35±2)%</td>
<td>(5.4±0.9)%</td>
</tr>
<tr>
<td>all cuts</td>
<td>(3.98±0.03)×10⁻³</td>
<td>(2.8±0.2)×10⁻⁴</td>
<td>(6±1)×10⁻⁷</td>
</tr>
</tbody>
</table>
5.2 A New Channel: $H \rightarrow ZZ \rightarrow \mu\mu\nu\nu$

Figure 5.13: Distributions of the main kinematic variables after the preselection cuts for signal and background processes: transverse momentum distributions of the first (above, left) and second (above, right) muon, transverse momentum (center, left) and pseudorapidity (center, right) of the $Z \rightarrow \mu\mu$ boson, opening azimuthal angle between the two muons (below, left) and $E_T$ distribution (below, right). All the histograms have the same arbitrary normalization.
Figure 5.14: $p_T(\mu\mu)/E_T$ distribution for signal and background processes after the preselection cuts (left). All the histograms have the same arbitrary normalization. Cut efficiency as function of the $p_T(\mu\mu)/E_T$ threshold. The statistical errors are reported.

Figure 5.15: Overall background efficiency against signal efficiency for various configurations of track counting veto after the preselection cuts. The left plot refers to a Higgs mass of 200 GeV, the right plot refers to a Higgs mass of 500 GeV. The statistical uncertainties are reported. The signal efficiency is larger than the square root of the background efficiency, inducing a gain in significance, only for the points below the shadow black line.
5.2 A New Channel: $H \rightarrow ZZ \rightarrow \mu\mu\nu$

Figure 5.16: Distributions of the isolation variables defined in eq. 5.1 for the muon with smaller transverse momentum in signal and background processes after the preselection cuts (left). All the histograms have the same arbitrary normalization. Cut efficiency as function of the isolation threshold (right). The statistical uncertainties are reported.

Figure 5.17: Distributions of the transverse IP significance of the muon with smaller transverse momentum in signal and background processes after the preselection cuts (left). All the histograms have the same arbitrary normalization. Efficiency of a possible cut on this variable (right): on the x axis the cut value is indicated (e.g., cut = 6 means $|d_0/\sigma(d_0)| < 6$). The statistical uncertainties are reported.
5.2.5 Results

Because of the presence of two neutrinos in the final state, the Higgs mass cannot be reconstructed in the $H \rightarrow ZZ \rightarrow \mu\mu\nu\nu$ channel, however alternative variables can be considered [111, 112], analogously to the azimuthal opening angle between the two charged leptons in the $H \rightarrow WW \rightarrow \ell\nu\nu\nu$ case.

Signal events are predicted to give a peak in their distribution versus the transverse mass $M_T$, defined in terms of the detected $Z \rightarrow \mu\mu$ boson by

$$M_T(Z) = 2 \sqrt{p_T^2(\mu\mu) + M^2(\mu\mu)} \tag{5.2}$$

Beside the reconstructed $Z \rightarrow \mu\mu$ boson, signal events contain also information about the second $Z$ boson through the $E_T \sim p_T(\nu\nu)$, modulo measurement errors and occasional extra neutrinos from the decay of spectator hadrons. This information can be usefully incorporated in the two-body transverse mass of the pair of $Z$ bosons, defined by

$$M_T^2(Z_1, Z_2) = \left[ \sqrt{p_T^2(\mu\mu) + M^2(\mu\mu)} + \sqrt{p_T^2(\nu\nu) + M^2(\mu\mu)} \right]^2 - \left[ \vec{p}_T(\mu\mu) + \vec{p}_T(\nu\nu) \right]^2 \tag{5.3}$$

If the Higgs boson is produced longitudinally (i.e., $\vec{p}_T(H) = \vec{p}_T(\mu\mu) + \vec{p}_T(\nu\nu) = 0$), the two transverse mass formulas above are expected to have similar shape and same discriminant power. However, in events where the Higgs boson is produced with significant transverse momentum (characterized by a transverse boost $\beta_T$), the one-body transverse mass $M_T(Z)$ distribution receives corrections of order $\beta_T$ whereas the corrections to the $M_T(Z_1, Z_2)$ distribution are only of order $\beta_T^2$ [113]. Hence we expect the peak in the latter distribution to remain much sharper than the peak in the former, after the effects of Higgs transverse momentum have been included. In Fig. 5.18 the two transverse mass distributions are compared, confirming this expectation.

The two-body transverse mass distribution $M_T(Z_1, Z_2)$ is therefore the preferred one to search for a signal excess over the background, modulo systematic errors related to the $E_T$ measurement. In Fig. 5.19 the number of signal and background events with 1 fb$^{-1}$ of integrated luminosity as a function of $M_T(Z_1, Z_2)$ is shown. All the selection cuts are applied, the significance can be computed as the ratio of the signal events over the square root of the background events in a given transverse mass range, depending on the Higgs mass. The number of signal and background events and the corresponding significance for 1 fb$^{-1}$ of integrated luminosity are listed in Table 5.6. From the numbers quoted here, the luminosity needed for the Higgs evidence or the Higgs discovery can be computed. An integrated luminosity of about 12.5 fb$^{-1}$ (35 fb$^{-1}$) is
5.2 A New Channel: $H \rightarrow ZZ \rightarrow \mu\mu\nu\nu$

Figure 5.18: Comparison between the two Higgs transverse mass distributions defined in equations 5.2 and 5.3 for a Higgs mass of 200 GeV (left) and 500 GeV (right). All the selection cuts are applied and the statistical uncertainties are reported.

Figure 5.19: Number of signal and background events with 1 fb$^{-1}$ of integrated luminosity as a function of the Higgs transverse mass defined in eq. 5.3. The background processes are stacked.
needed for a significance of 3 (5) in this channel with a Higgs mass of 500 GeV. The case with smaller Higgs mass is instead overwhelmed by the $Z$+jets background so that about four and a half years of high luminosity run of LHC ($10^{34}$ cm$^{-2}$ s$^{-1}$) must be exploited for a Higgs evidence in this channel.

**Table 5.6:** *Number of signal and background events and corresponding significance for 1 fb$^{-1}$ of integrated luminosity. The significance is computed as signal over square root of background and the MC statistical uncertainties are reported.*

<table>
<thead>
<tr>
<th></th>
<th>$150 &lt; M_T(H) &lt; 250$ GeV</th>
<th>$M_T(H) &gt; 400$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>signal MH200</td>
<td>22.4 ± 0.2</td>
<td>-</td>
</tr>
<tr>
<td>signal MH500</td>
<td>-</td>
<td>4.96 ± 0.08</td>
</tr>
<tr>
<td>$Z$+jets</td>
<td>24003 ± 165</td>
<td>31 ± 5</td>
</tr>
<tr>
<td>$t\bar{t}$+jets</td>
<td>202 ± 7</td>
<td>0.6 ± 0.4</td>
</tr>
<tr>
<td>$W$+jets</td>
<td>33 ± 7</td>
<td>0</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>78 ± 3</td>
<td>2.6 ± 0.5</td>
</tr>
<tr>
<td>$WW$</td>
<td>51 ± 3</td>
<td>0.4 ± 0.2</td>
</tr>
<tr>
<td>backgrounds</td>
<td>24367 ± 165</td>
<td>34 ± 5</td>
</tr>
<tr>
<td>significance</td>
<td>0.143 ± 0.001</td>
<td>0.85 ± 0.06</td>
</tr>
</tbody>
</table>

At high Higgs mass this channel is therefore very promising while for low and intermediate Higgs mass this can be an interesting control channel, once the Higgs will be discovered. In this case the Higgs mass will be already known, hence a likelihood approach will be suitable.

A likelihood is built to enhance the discriminant power between background and signal with Higgs mass of 200 GeV. The variables which show the largest differences between signal and $Z$+jets dominant background are exploited: pseudorapidity of $Z \rightarrow \mu\mu$, opening azimuthal angle between muons, $E_T$, Higgs transverse mass as computed in equations 5.2 and 5.3. The likelihood distribution is shown in Fig. 5.20 for signal with Higgs mass of 200 GeV and background. By requiring the likelihood output smaller than 0.4, the signal significance improves (≈ 0.211 with 1 fb$^{-1}$), as reported in Table 5.7. With this strategy about 200 fb$^{-1}$ of integrated luminosity are needed for an evidence of Higgs mass of 200 GeV in this channel, which correspond to two years of high luminosity run of LHC ($10^{34}$ cm$^{-2}$ s$^{-1}$).
5.2 A New Channel: $H \rightarrow ZZ \rightarrow \mu\mu\nu\nu$

Figure 5.20: Likelihood distribution for signal and background with the same arbitrary normalization (left). Number of signal and background events with 1 fb$^{-1}$ of integrated luminosity as a function of the likelihood variable (right). The MC statistical uncertainties are reported.

Table 5.7: Number of signal and background events and corresponding significance for 1 fb$^{-1}$ of integrated luminosity. The significance is computed as signal over square root of background and the MC statistical uncertainties are reported.

<table>
<thead>
<tr>
<th>Category</th>
<th>likelihood$&gt;0.4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>signal MH200</td>
<td>13.5 ± 0.2</td>
</tr>
<tr>
<td>$Z$+jets</td>
<td>4020 ± 62</td>
</tr>
<tr>
<td>$tt$+jets</td>
<td>196 ± 7</td>
</tr>
<tr>
<td>$W$+jets</td>
<td>28 ± 7</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>60 ± 3</td>
</tr>
<tr>
<td>$WW$</td>
<td>33 ± 2</td>
</tr>
<tr>
<td>backgrounds</td>
<td>4350 ± 63</td>
</tr>
<tr>
<td>significance</td>
<td>0.205 ± 0.003</td>
</tr>
</tbody>
</table>
5.2.6 Main Systematics

This analysis is performed with a realistic scenario of detector performances. Misalignment and miscalibration correspondent to the precision reachable with an integrated luminosity of 100 pb$^{-1}$ are considered.

Statistical uncertainties due to limited MC statistics are reported in previous tables. Experimental and theoretical systematics play a key role in this analysis where no clear Higgs mass peak is available. The dominant systematic uncertainties are expected to come from the following sources.

**Luminosity** The uncertainty coming directly from LHC machine estimation is about 20% while the online luminosity monitors of CMS should reach a precision of 10%. The offline estimation of the integrated luminosity can rely on $\mu\mu$ and $ee$ Drell-Yan events [114]. The numbers of accepted events in the two final states, after correcting for background and selection efficiency, agree within 2%. Using the most recent PDF set and NNLO cross section calculation, the total integrated luminosity can be computed. Combining the uncertainties, a final uncertainty of about 10% on the integrated luminosity is expected.

**PDF** The PDF uncertainty is \(\sim 5\%\) on the dominant $Z$ background [5, 67] and \(\sim 10\%\) on the Higgs signal [115].

**Missing Transverse Energy** Uncertainties on the $E_T$ measurement have large impact on this analysis because the most powerful cut against the $Z+\text{jet}$ dominant background relies on $E_T$. The $E_T$ is also exploited to compute the Higgs transverse mass.

The $E_T$ resolution can be measured from data using a sample of $Z \to \mu\mu$ events with one muon artificially dropped. The $E_T$ distribution from these $Z$ events can be compared with the $E_T$ distribution obtained from MC in $W \to \mu\nu$ events. After having rescaled for the $M_W/M_Z$ ratio and having re-weighted to take into account the different kinematic of muons from $W$ and $Z$ decay, the remaining difference between the two distributions gives the estimation of the $E_T$ systematics. A precision of about 5% is expected when the detector will come to stable operation [5, 116].

To estimate the impact of this uncertainty, the full analysis workflow is performed after having introduced a 5% smearing on the $E_T$ measurement. The differences on the final numbers of signal and background events are reported in Table 5.8.

**Background normalization** The systematic uncertainty due to the normalization of the two main backgrounds ($Z+\text{jets}$ and $ZZ$) is estimated in the following.
5.2 A New Channel: $H \rightarrow ZZ \rightarrow \mu\mu\nu$

- $Z$+jets normalization from data.
  A careful strategy to measure the overall normalization of the $Z$+jets background from data is needed. This can be done identifying a background control region where the $Z$+jets background dominates over the other background and signal processes. Then, the expected number of $Z$+jets events in the signal region can be estimated using this formula:

$$B^{signal\ region} = \frac{B^{signal\ region}_{MC}}{B^{control\ region}_{MC}} \times B^{control\ region}_{data} \quad (5.4)$$

where $B_{MC}$ is the number of $Z$+jets events in each region given by the MC and $B_{data}$ is the number of $Z$+jets events measured from data.

The most effective cut against $Z$+jets background is the cut on $E_T$ (> 25 GeV), inverting this cut a quite clear sample of $Z$+jets can be obtained. The pollution from the other backgrounds and the signal in this control region is negligible (from MC we get 69 events against 284026 $Z$+jets events for 1 fb$^{-1}$, i.e., 0.02% of contamination). Also the statistical error of $B^{control\ region}_{data}$ will be very small (0.2% with 1 fb$^{-1}$ of data).

The control region is defined by inverting the $E_T$ cut and keeping all other analysis cuts unchanged. The MC extrapolation from the control region to the signal region ($\frac{B^{signal\ region}_{MC}}{B^{control\ region}_{MC}}$) is therefore affected by the systematics on $E_T$. The $E_T$ spectrum should be calibrated from data at 5% level, as already explained. This would correspond to an uncertainty of 2% on the $B^{signal\ region}_{MC}$ and an equivalent uncertainty can be estimated on $B^{control\ region}_{MC}$.

Combining all the systematic uncertainties on $B^{control\ region}_{MC}$, $B^{signal\ region}_{MC}$ and $B^{control\ region}_{data}$, the final uncertainty on $B^{signal\ region}_{MC}$ is computed (3%).

- $ZZ$ normalization from data.
  One would apply a similar normalization strategy also to the $ZZ$ background, unfortunately there is no any kinematic region where the $ZZ$ background dominates, because the contribution from single-$Z$ background is always large.

Another possibility is relying on the relative normalization between single and double $Z$ production. A control region can be defined applying only the cuts on muons, without taking into account the $E_T$. In this control region the number of $ZZ$ events can be computed from data exploiting the single-$Z$ normalization:

$$N^{control\ region}_{ZZ} = N^{data}_{Z} \times \frac{\sigma_{ZZ}}{\sigma_Z} \times \frac{\epsilon^{MC}_{ZZ}}{\epsilon^{MC}_{Z}} \quad (5.5)$$
where \( N_{Z}^{data} \) is the number of single-\( Z \) events in the control region measured from data, \( \sigma_{ZZ}/\sigma_{Z} \) is the ratio of the cross sections of the two backgrounds and \( \epsilon^{MC} \) is the selection efficiency of each of the two processes computed with the MC in the control region. In the ratio of the two efficiencies the uncertainties due to muon efficiency, resolution and scale, which are however quite small as discussed in the following, partially cancel out. The uncertainty on the cross section ratio is also very small because the large theoretical uncertainty, which is due to PDFs, mostly cancels out. \( N_{Z}^{data} \) can be approximated to the total number of background events in the control region, being the pollution from other background processes (\( ZZ \) included) of the order of 0.2%. The statistical uncertainty of \( N_{Z}^{data} \) is also very small (0.15% with 1 fb\(^{-1} \) of data).

The signal region is obtained by adding the \( E_{T} \) related cuts (\( E_{T} > 25 \) GeV, \( p_{T}(\mu)/E_{T} < 1.6 \), \( M_{T}(Z_{1},Z_{2}) > 400 \) GeV) to this control region. Therefore the extrapolation of the \( ZZ \) background from one region to the other:

\[
N_{Z}^{signal\, region} = \frac{N_{Z}^{signal\, region\, MC}}{N_{Z}^{control\, region\, MC}} \times N_{Z}^{control\, region}
\]

(5.6)

is dominated by the \( E_{T} \) uncertainty. The already mentioned 5% uncertainty on the \( E_{T} \) distribution would correspond to 4% uncertainty on \( N_{Z}^{signal\, region\, MC} \) and it has no impact on \( N_{Z}^{control\, region\, MC} \) where the \( E_{T} \) is not considered at all.

Combining all the discussed uncertainties a final error of about 4% is expected on the \( ZZ \) normalization.

**MC modeling of single-\( Z \) transverse momentum** The single-\( Z \) production is the dominant background and the distribution of the \( Z \) transverse momentum affects the selection cut on \( p_{T}(\mu)/E_{T} \), the Higgs transverse mass distribution and other variables (\( \eta_{Z}, \Delta \phi(\mu \mu) \)) used to build the final likelihood in case of low Higgs mass. The analysis results obtained with PYTHIA and AlpGen (see Sec. 5.2.3) are compared in Fig. 5.21. In the intermediate \( Z \) \( p_{T} \) region, which is selected for the Higgs analysis at low mass, PYTHIA gives a larger number of events with respect to AlpGen. In the high momentum region, selected in case of high Higgs mass, PYTHIA gives a much smaller number of events.

However it should be noted that the present theoretical knowledge of the \( Z \) background is much more advanced with respect to the MC event generator used in this analysis. The differential computation of the perturbative QCD corrections is well established up to the NNLO and the perturbative series show good convergence properties [64]. Also the contribution of the electroweak
5.2 A New Channel: $H \to ZZ \to \mu\mu\nu\nu$

![Graphs](image)

**Figure 5.21:** Comparison between $Z$ background sample generated by PYTHIA and AlpGen: $Z$ transverse momentum at generator level after HLT and skimming (above), distribution of the reconstructed Higgs transverse mass (below, left) and likelihood distribution (below, right) after the full analysis workflow.

NLO has been recently addressed [65, 66]. Moreover the distribution of the $Z$ transverse momentum in single-$Z$ events will be measured from LHC data with high precision thanks to the huge available statistics. Therefore, at the integrated luminosity interesting for this analysis ($> 10 \text{ fb}^{-1}$), we should expect a very good control of the shape of this distribution.

**Muon efficiency, resolution and scale** All these quantities can be measured from data as explained in Chapter 4. After having applied the calibration procedure explained there and having used the tag-and-probe method to estimate the efficiencies from data, the residual systematics due to efficiency, misalignment and B field distortion are very little ($<1\%$ on $Z \to \mu\mu$ cross section).

**Jet energy scale and jet reconstruction efficiency** This systematics is not expected to have any impact on this analysis since no jet veto is applied. Although jets can affect the muon isolation cut, however the isolation cut effi-
ciency can be computed through the tag-and-probe method.

The variation of the number of signal and background events due to the systematics which are expected to have larger impact on the analysis are reported in Table 5.8. Only the case of 500 GeV Higgs mass is considered for the signal. Also the MC statistical uncertainty is indicated.

Table 5.8: Main uncertainties on the number of signal and background events. In the procedure of background normalization described in the text the PDF and luminosity uncertainties cancel out.

<table>
<thead>
<tr>
<th>Sources</th>
<th>signal MH500</th>
<th>background</th>
</tr>
</thead>
<tbody>
<tr>
<td>luminosity</td>
<td>10%</td>
<td>-</td>
</tr>
<tr>
<td>PDF uncertainties</td>
<td>10%</td>
<td>-</td>
</tr>
<tr>
<td>$E_T$ modeling</td>
<td>0.3%</td>
<td>2%</td>
</tr>
<tr>
<td>normalization</td>
<td>-</td>
<td>3%</td>
</tr>
<tr>
<td>MC statistics</td>
<td>1.6%</td>
<td>15%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>14.2%</strong></td>
<td><strong>15.4%</strong></td>
</tr>
</tbody>
</table>

20000 pseudo-experiments are generated in the null hypothesis of background only and in the signal hypothesis with Higgs mass of 500 GeV. The number of signal and background events expected with 1 fb$^{-1}$ of integrated luminosity are smeared with the systematic uncertainties listed in Table 5.8. The results are reported in Fig. 5.22. The signal hypothesis can be tested with 1 fb$^{-1}$ of data with a confidence level of 22.34% which correspond to 0.76 standard deviations. If the significance goes like $\sqrt{L}$, then about 15.5 fb$^{-1}$ (43 fb$^{-1}$) would be needed for a Higgs evidence (discovery) in this channel.
Figure 5.22: 20000 pseudo-experiments in the null hypothesis of background only and in the signal hypothesis with Higgs mass of 500 GeV. The number of signal and background events expected with 1 fb$^{-1}$ of integrated luminosity are smeared with the systematic uncertainties listed in Table 5.8.
Summary

This thesis describes the various steps along the road going from the single hit measurement in the Drift Tube detector to the analysis of final states with muons for the Higgs search.

The Drift Tube system is a time measuring device. A careful calibration procedure is needed to compute, from these time measurements, the hit positions in the detector. Then, the so-called “local reconstruction” is in charge of building track segments by fitting all the hit measurements in each Drift Tube chamber.

I developed the algorithms for calibration and local reconstruction and I studied their performances in simulated p–p collisions and with real cosmic muons. In the first case, a very good resolution is achievable on the track segment position (90 $\mu$m for the bending coordinate and 120 $\mu$m for the non-bending one) and on the track segment angle (0.7 mrad on the azimuthal angle and 6 mrad on the polar angle). In the second case, the Drift Tube performances are strongly affected by the angular distribution and the flat arrival time distribution of cosmic muons: the results obtained from cosmic data are not directly applicable to muons in p–p collisions, which come from the interaction point and are synchronous with the LHC clock. However, the big amount of cosmic data collected during the detector commissioning has been useful to test the hardware functionality. For this purpose the application of calibration and local reconstruction algorithms, modified to match the particular conditions of cosmic muons, has been crucial. On the other hand, the commissioning exercise, starting from the local runs with the Drift Tubes running alone, going to the Magnet Test and Cosmic Challenge with the integration of a few percent of the muon system, up to the global runs with increasing integration of the full CMS detector, provided a unique opportunity to test the algorithms in a detector environment of increasing complexity. This test not only allows to debug and optimize these algorithms, but also gives a boost to the definition of reliable and automatic computing and software procedures for the application of these algorithms in realistic experimental conditions.

The second step in the muon detection is the full track reconstruction, possibly matching the information of the muon system with that coming from the
inner tracker. At this stage, the resolution of the kinematic parameters of the reconstructed muons can be affected by several sources of smearing and biases due to detector effects like misalignment, magnetic field distortion and multiple scattering. A dedicated algorithm to measure, and possibly correct, these effects is presented in this thesis: this calibration procedure is able to measure the muon momentum scale and the muon momentum resolution from data, relying on well-known di-muon resonances ($J/\psi$, $\Upsilon$, $Z$).

The calibration algorithm has been applied to the experimental case of the $Z$ cross section measurement, showing excellent results concerning the systematics in the $Z$ acceptance calculation. The acceptance of the offline cuts increases of 1.7% by applying the muon calibration algorithm, in the meanwhile the systematics due to the tracker misalignment, the muon system misalignment and the magnetic field distortion decreases from 3.5%, 3.2% and 1.8%, respectively, to 0.9%, 0.3% and 0.5%.

Once the muons have been reconstructed and calibrated with the best achievable precision, they play a lead role in the Higgs search in the intermediate mass region ($m_H > 140$ GeV), where the favorite channels are $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ and $H \rightarrow ZZ \rightarrow 4\ell$. The discovery power of both these channels decreases in the high mass region: the first one is not anymore suitable for $m_H > 250$ GeV because of kinematic reasons, the second one has a very low branching ratio and therefore it is strongly affected by the exponential decrease of the Higgs production cross section with the increasing of the Higgs mass. For these reasons, in the high Higgs mass region the semileptonic final states are usually exploited, which are however overwhelmed by the $V+\text{jets}$ background.

I have studied a new, fully leptonic final state: $H \rightarrow ZZ \rightarrow \mu\mu\nu\nu$, which can give an important contribute to the Higgs discovery in the mass region around 500 GeV. This channel has a branching ratio about 10 times larger than $H \rightarrow ZZ \rightarrow 4\mu$, it has the same final state of $H \rightarrow WW \rightarrow \mu\nu\mu\nu$ but a larger amount of background is expected because the huge $Z+\text{jets}$ contribution cannot be rejected by asking the di-muon mass being far away from the nominal $Z$ mass. Nevertheless, the analysis results, also including the systematic uncertainties, are very promising: an integrated luminosity of about 15.5 fb$^{-1}$ is enough for the evidence in this channel of a Higgs with mass of 500 GeV. The main uncertainty at this moment is due to the limited statistics of the available MC samples. This uncertainty is included in the systematic errors, therefore the needed integrated luminosity can be further reduced in future studies with larger background samples. Moreover, the final state with electrons can also be considered, thus doubling the discovery power.

This is the first exploratory study in this channel. The main open issue is presently the MC modeling of the distribution of the $Z$ transverse momentum. Two MC generators are compared showing large discrepancies, definitely larger
than the experimental uncertainties which can be controlled quite well thanks to the muon calibration procedure previously described. Given the importance of the single-$Z$ production, not only as a background for the Higgs search, but also as a test of the Standard Model at an unprecedented energy scale, the measurement of the inclusive distribution of the $Z$ transverse momentum is strongly advised, as soon as the CMS will collect the required statistics.
Vorrei iniziare nominando chi NON voglio ringraziare: questo governo cieco o in malafede ed anche tutti i governi succedutisi in questi anni che hanno cancellato un pezzo alla volta, anno dopo anno, il mio futuro in Italia, non solo come ricercatrice, grazie ai ripetuti tagli alla ricerca, ma anche più in generale come giovane lavoratrice, grazie alla legge Biagi e a tutto quello che ne è seguito.

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